A Study of Functional Recovery Following Anterior Cruciate Ligament Reconstruction

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A thesis submitted for the degree of doctor of philosophy

Year of presentation: 2015

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Acknowledgements

The incredible journey to complete this PhD thesis has been truly life changing and only possible with the incredible support of many great people.

First thanks must go to the patients and volunteers that participated in this process without which it would not have been possible. I thank you all for your time and commitment.

Thanks then to my supervisors Prof Robert van Deursen and Dr Valerie Sparkes and the research team at the school of healthcare sciences. The passion that they have for rehabilitation science and vision to create a legacy of clinical academics capable of progressing rehabilitation science at the intervention interface has been inspirational. Dr Kate Button and Dr Paulien Roos have been integral to the development of myself and of this project and I thank you both for your patience and contributions. To my fellow PhD students at healthcare sciences and the Arthritis Research centre, I thank you for your support and advice; special thanks to Rebecca Hemming, Mike Smith and Paul Adamson.

Being a fellow of RCBC Wales has been a truly wonderful experience. Prof Donna Mead (OBE), Dr Mark Llewelyn and everyone in the 'community of scholars' should be congratulated for their part in creating such a wonderful and diverse fellowship scheme for allied health professionals.

Aneurin Bevan University Health Board have supported this project throughout, special thanks must go to Mrs Fiona Seeney who fought my corner and Mrs Julie Fall who supported the case for part time study. To my clinical colleagues in RGH and beyond, I thank you for your patience and support during this process; I hope that I have managed to pass on something useful and inspired greater interest in rehabilitation science.

Finally, but certainly not least to friends and family, you all know who you are. You have been encouraging, patient and interested beyond any reasonable expectation, without which I would not have reached this point. I apologise for the time I have missed spending with you, the distracted (and sometimes grumpy) moods and the endless wittering about stuff you have no reason to be interested in. Without your amazing support and patience this thesis never would have been completed – I thank you the most.

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Abstract

Introduction
Anterior cruciate ligament reconstruction (ACLR) and rehabilitation is an accepted intervention for non-coping ACL injured subjects. There is an expectation from ACL injured subjects and the international clinical community that ACLR should enable recovery to pre-injury knee function, activity performance and participation. However, few studies use comprehensive methods to assess this expectation and the reality seems to be a highly variable and often incomplete recovery that is difficult to predict. Improved understanding of recovery of these subjects may identify targets for novel rehabilitation interventions that improve outcomes.

Methods
Prospective longitudinal data were collected from 74 ACL injured subjects before surgery and on 5 occasions during the first year following ACLR. Data from a matched healthy group (n=61) were used to define healthy normative values. Outcome measures included; Structure (arthroscopic and MRI findings), Function (IKDC SKF, Lysholm, VAS pain), Activity (2D digital video motion analysis of performance and strategy variables during gait, single leg squat and hop for distance) and Participation (Tegner). Group differences and recovery were assessed with inferential statistics; regression methods identified predictors of recovery.

Results
These ACL injured subjects were highly symptomatic non-copers with a prolonged period between injury and surgery. There were statistically and clinically significant deficits from healthy in all outcome measures before surgery, which improved one year following ACLR; however the majority failed to fully recover. Bilateral deficits in activity performance and strategy were identified during all three functional activities. Recovery at one year was not predicted by any of the outcome measures in the pre or post-operative period. However, activity performance at one year was predicted by pre-operative and early post-operative gait velocity and squat depth.

Conclusions
Whilst these highly symptomatic non-coping ACLD subjects benefited from ACLR and rehabilitation, expectations of full recovery by one year proved unrealistic for most. Pre-operative deficits appear to be too large for current interventions to overcome. Early diagnostics, classification and intervention should be considered to reduce pre-operative impairments. Bilateral and hierarchical deficits in activities suggest that further development of task oriented rehabilitation strategies should be built on biomechanical and motor control / learning theories to improve outcomes. Utilising technology to facilitate greater engagement in rehabilitation and increasing frequency and intensity of rehabilitation interventions should be considered. Further development of clinically applicable methods to measure and provide real time feedback on both performance and strategy in functional activities are therefore required.

Introduction

Anterior cruciate ligament (ACL) injury is common in the recreationally active population. Whilst some individuals may cope or adapt following injury (Noyes, 1983; Rudolph et al, 1998) many experience functional instability and participation restrictions (Rudolph et al., 1998). For these non-coping individuals, ACL reconstruction (ACLR) and rehabilitation offers an opportunity to improve knee stability and participation. There is now an expectation from ACL injured subjects and the international clinical community that ACLR and rehabilitation will facilitate a return to pre-injury status of knee function, activity performance and participation (Heijne et al., 2008; Thorstenssen et al., 2009; Lynch et al., 2015). There is high quality data from both meta-analysis (Biau et al., 2007; Freedman et al., 2003) and national registries (Lind et al., 2009; Ahlden et al., 2012; Granan et al., 2012) demonstrating the benefits of ACL reconstruction and rehabilitation. However, there are few studies which use appropriate methods to adequately assess the expectation of full recovery. The reality seems to be variable outcome and often incomplete recovery (Heijne et al., 2008; Ardern et al., 2011; Hill and O'Leary, 2013; Herrington et al., 2013) that is difficult to predict (de Valk et al., 2013). Rehabilitation interventions are an important part of the care pathway for ACL injured subjects (Myer et al., 2006). Systematic reviews provide clinicians with guidance and support for the use of both strength and neuromuscular training programmes (Wright et al., 2008; van Grinsven et al., 2010; Kruse et al., 2012; Lobb et al., 2012). However, further developments in the field may improve both short and long term outcomes following ACLR. Modern criterion based rehabilitation methods are gaining support in the literature (Adams et al., 2012, Kvist, 2005, Myer et al., 2012), however further investigation of clinical milestones are required to guide application in the clinic. Developing a greater understanding of functional recovery in ACL injured and reconstructed subjects will enable the identification of these milestones and targets for novel rehabilitation strategies that may improve outcome and facilitate recovery following ACLR.

Theories of dynamic knee stability have been applied to explain the differential response following both ACL injury and reconstruction (Solomonow and Krogsgaard, 2001; Williams et al., 2001; Rudolph et al., 2001; Swanik et al., 2004). These theories suggest that the stability of a joint is dependent upon appropriate coupling of the passive and active stability systems

(Needle et al., 2014). A deficiency in the passive restraints following injury might therefore be compensated for by an appropriate and coordinated response of the neuromuscular system. Motor control and motor learning theories are therefore considered important to facilitate this response and generate adaptations in the sensorimotor system that promote recoupling of the stability systems and enable recovery (Needles et al., 2014; Hodges and Tucker, 2011; Banjaminse et al., 2015). A broad spectrum of sensorimotor impairments and adaptations has been demonstrated following ACL injury and reconstruction (Ageberg, 2002; Ingersoll et al., 2008) the extent of which may be one explanation for variable recovery. Importantly these factors may be targets for novel developments in rehabilitation strategies.

Recent advances in ACLR rehabilitation propose a criterion based approach (Nyland et al., 2010; Adams et al., 2012, Myer et al., 2012), with testing of functional tasks of different complexities used as clinical milestones to inform the progression of rehabilitation and return to activity and participation. Walking gait is a simple task and hop for distance a more complex one which have been proposed as clinical milestones (Kvist et al., 2005; Risberg et al., 2009; Adams et al., 2012; Myer et al., 2012) which are currently applied as performance measures (Gustavson et al., 2006; Thomee et al., 2012; Logerstedt et al., 2012). The application of these milestones is however limited by a lack of understanding of recovery of these tasks following ACLR and their capability to act as modifiable predictors of successful outcome. These measures are also dominated by the use of symmetry indices (Logerstedt et al., 2013), which are being increasingly criticised (Reid et al., 2007; Bent et al., 2009; Thomee et al., 2012; Herrington et al., 2013). Recent advances in biomechanics have defined altered and compensated movement strategies (Augustsson et al., 2006; Deneweth et al., 2010; Oberlander et al., 2012; Roos et al., 2013) that can be used to differentiate the response to injury and recovery following reconstruction. Whilst these are likely to be useful aids for rehabilitation milestones, the available methods limit application within the clinic. Several tests based upon observation and categorisation (Trullson et al., 2010; Padua et al., 2009) have shown promise, however with rapidly advancing technology biomechanical analysis in the clinic should be possible and requires further investigation. Further development and inclusion of clinically applicable measures of task performance and strategy will enable the identification of measurable clinical milestones based upon their ability to predict successful outcome.

Since 2003, a Physiotherapy led clinical review service within Aneurin Bevan University Health Board (ABUHB), South Wales, UK, has been assessing and monitoring clinical outcomes, before and over the first two years following ACLR. Since there was no specific service provision for acute knee injuries within ABUHB, most subjects present a considerable time after injury, seeking intervention due to a lack of recovery. In comparison to studies with early investigation and intervention, this group seem to be highly symptomatic and may therefore represent a different sub-group of subjects undergoing ACLR than has previously been reported in the literature. Noyes (1983) described a classification system of copers and non-copers that has been further developed and ingrained in the ACL literature (Snyder-Mackler et al., 1997, Rudolph et al., 1998). Current criteria (Rudolph et al., 1998) classify subjects as non-copers and recommend surgical intervention after just 1 episode of functional instability. The subjects under investigation are therefore likely to represent the severely symptomatic or worse off of the non coping classification and represent an opportunity to study the more symptomatic ACLD subject undergoing ACLR. The observations made when collecting patient reported and clinical data from this service mirrored those of the wider literature, with variable and often incomplete functional recovery and adapted participation. Improving the understanding of functional recovery in order to inform the development of ACLD and ACLR rehabilitation in this patient group is the motivation behind this thesis.

Continued study of functional recovery following ACLR is required to understand the variable and incomplete recovery and inform the development of rehabilitation to improve outcomes for ACLD and ACLR subjects. The ACLR clinical review service at ABUHB offers the opportunity to collect longitudinal data on the same subjects before and at multiple occasions over the first year following ACLR. Combined with a matched healthy control group and methods of clinical significance, the current gap in the understanding of recovery to healthy levels can be defined and explored. Using a longitudinal observational methodology and clinically applicable measures, this study will define pre-operative deficits and post-operative recovery of outcomes from all domains of the WHO ICF (structure, function, activity and participation). Particular focus will be on the development and use of biomechanical measures of performance and strategy during commonly utilised functional tests. Predictors of outcome at 1 year post-operatively will be identified and defined as clinical milestones that can be used to inform criterion based rehabilitation progressions in this subject group.

Literature review

In order to inform the development of this study of functional recovery following ACLR, the literature review focuses on three main elements. Firstly, the process of ACLR and rehabilitation is considered, including dilemmas in selecting subjects, content of rehabilitation and appropriate methods for measuring success. Next, the theories of dynamic knee stability and motor adaptation are applied to explain variable and often incomplete recovery following ACL injury that might inform the development of novel rehabilitation approaches. Finally, a thorough assessment of the current understanding of deficits and recovery of measures from each domain of the WHO ICF informs the development of novel measurement tools and data collection for this longitudinal study of functional recovery following ACLR.

Search strategy

Searches were conducted in OVID to search Medline, EMBASE, AMED and cinahl databases. Automatic updates were requested monthly for the period up until January 2015. The following search terms were entered (allowing for changes depending upon database MESH terms) and combined with AND terms for different sections of the review process.

Anterior Cruciate Ligament OR ACL OR ACLD OR ACLR

Healthy OR Normal

Recovery OR return OR resumption OR restoration

Rehab* OR physio* OR physiotherapy

Knee function OR symptoms OR pain

Functional test* OR activity test*

Gait OR walk* OR gait velocity OR step length OR cadence

Squat* OR single leg squat

Hop* OR SLHD OR Hop for distance

Land* OR landing strategy

Motion analysis OR movement analysis OR biomechanics OR kinematics OR kinetics

Video OR digital video OR 2D video

Participation OR sport OR return to sport

Treatment of ACL injury

Who should have ACL reconstruction?

Both surgical and rehabilitation pathways have been shown to be beneficial in the management of ACL injuries. However, the appropriate criteria upon which to base decisions for the individual remains a matter of considerable debate. Within clinical practice two very different decision making schemes exist. The surgical risk factor (SURF) categorises those with high activity demands into early surgical reconstruction (Fithian et al. (2005) and those with low demands to rehabilitation. The Delaware screening tool (Fitzgerald et al., 2001) uses a more complex combination of patient reported outcomes (PROMs) and functional testing to define copers and adaptors as candidates for rehabilitation and non-copers as candidates for ACLR. The large scale surveys of orthopaedic surgeons from Marx et al. (2001), McRae et al. (2011) and Cook et al. (2008) identified significant variations in the indicators for ACLR. However they also suggest that present practice is more closely aligned to Fithian's model. Although pre-injury activity level was consistently an indicator for ACLR, there are substantial differences in other indicators such as time and effort dedicated to conservative management and functional performance testing, prior to considering ACLR. McRae et al. (2011) found agreement (defined as >80%) that giving way with ADL and sports activities and a repairable meniscal tear were indicators for ACLR. This variability of selection of candidates for ACLR will lead to heterogeneity in the ACLR population which may explain some of the variability in outcomes following ACLR. The subjects within the ABUHB service are almost all self-selected due to being highly symptomatic with inadequate recovery and are and therefore likely to meet the non-coper criteria. In contrast to this, Button et al. (2006) identified 17% copers and 45% adaptors in a study within an acute knee screening service within the Welsh NHS, although some of these may meet Fithian's criteria for ACLR.

In recent years there has been a reawakening in the debate regarding the selection of operative and non-operative management of ACLD knees, centred on an RCT from Frobell et al. (2010). The very well conducted study randomised 121 young, active ACLD subjects to either early ACLR, or a programme of functional rehabilitation, with the option of delayed reconstruction should they choose. The study had found an effective solution to the ethical problem of denying a proven intervention (ACLR), simply by leaving the door open to that intervention should a subject chose. Just 23 of the 59 subjects randomised to the rehabilitation and delayed surgery group elected to proceed with surgery; the remaining 36 received rehabilitation alone. Functional outcomes, measured with the knee injury and osteoarthritis outcome score (KOOS), at a 2 year follow up demonstrated no significant differences, either between the original randomised groups, or post hoc groupings based upon the intervention received. The authors concluded that for young active individuals early surgical intervention offered no superiority over rehabilitation and optional delayed reconstruction.

The paper received substantial support (Love and Mohtadi, 2011; Fowler et al., 2011; Khan, 2010) for providing a unique insight into the positive short term effect of a purposive recommendation for rehabilitation with the option for delayed surgical intervention based upon patient choice and functional outcomes. However, there was also considerable criticism of the omission to discuss a higher rate of meniscal tears (Fowler, 2011; Love and Mohtadi, 2011; Burnstein, 2011) identified in the delayed surgery group. Certainly caution in reporting long term effects of this intervention is warranted and only long term follow up will determine if the management alters the course of degenerative disease in this sample. Burnstein (2011) was particularly interested in the higher incidence of meniscal injury reported in the rehabilitation group (35%) compared to the intervention group (23%) and produced a decision analysis which indicated that in order to prevent 1 meniscal tear in the delayed intervention group 5.25 of the groups subjects would have to undergo early surgical reconstruction. The cost of 1 meniscal tear therefore has to be valued, by the patients, surgeons and society, above the cost of 5.25 surgical reconstructions.

It seems likely that the debate of which intervention to select will continue. The reality most likely being that there are individuals who will do well with each of the current options and that identification of predictors to enable effective clinical decision making is the way forward. The Delaware criteria (Fitzgerald et al., 2001) offer a start for this process. Recent work from Eitzen et al. (2010) has provided support for this type of tool and proposed that greater influence is given to functional recovery in the decision to undertake ACLR. Their prospective study demonstrated that a pre-operative functional screening examination was better able to predict those that were referred on for surgical stabilisation than simple algorithms based upon pre-injury sport and passive instability. They suggest that investigation of functional tests as pre-operative predictors would further enhance the decision making schemes and enable patients to make more informed decisions about intervention selection.

ACLR rehabilitation

Recent improvements in the consistency of individualised and anatomically aligned ACLR, have led Myer et al. (2006) to suggest that differences in rehabilitation rather than surgery, may now better explain variance in outcomes following ACLR. Ongoing developments in rehabilitation are therefore required to maximise outcomes for the ACL injured population. Rehabilitation has gone through something of a revolution in recent decades (Myer et al., 2006). Traditional programmes encouraged initial immobilisation and slow progression on the basis of theoretical models of graft healing. This produced a one size fits all model with time from surgery as the primary guide for progression (Kvist, 2004). This changed during the 1990's as "accelerated rehabilitation" was adopted from the work of Donald Shelbourne, who was the first to abandon post-operative immobilisation in favour of early mobilisation and functional rehabilitation. This group demonstrated that there were no apparent deleterious effects on passive stability and that complications were reduced and return to sport enhanced (Shelbourne and Nitz, 1990; Shelbourne and Wilckens, 1990; Shelbourne et al., 1995; Shelbourne et al., 1992; Shelbourne et al., 1997). Further developments have led to a new paradigm which considers individual demands and functional capabilities as the primary driver of rehabilitation (Cascio et al., 2004; Kvist et al., 2004). Graft healing is still accounted for, however in the absence of methods to measure this phenomenon its influence is limited (Araujo et al., 2010). It has been appreciated that the temporal characteristics of healing and functional recovery follow different paths dependent upon multiple patient and injury specific factors (Myer et al., 2012, Araujo et al., 2012). The recent work of Myer et al. (2012) clearly demonstrates these differences in function and the lack of association between recovery and time from surgery. Adams et al (2012) refer to this change as a move from "surgery modified rehabilitation" designed to protect the healing graft at the expense of function, to "rehabilitation modified surgery" in which graft fixation is considered robust enough to allow early loading and enhanced functional recovery. The paradigm is however reliant upon the development of robust and measureable criteria on which progression can be based (Manal and Snyder-Mackler, 1996, van Grinsven et al., 2010, Adams et al., 2012). The current basis for these functional milestones is theoretical constructs and empirically defined predictors of recovery following ACLR (Adams et al., 2012). However there remains much to learn about the process of functional recovery and its relationship with successful outcome of ACLR. This is particularly the case with the broad spectrum of highly symptomatic non copers that appear to form the bulk of subjects within ABUHB and other NHS services. Vaguely described milestones such as ‘normal gait’ are not useful for therapists to apply with limited assessment methods in the clinic. Published measures of activity and functional performance are also highly reliant upon limb symmetry, the usefulness of which is being increasingly questioned within the literature (Thomeé et al., 2012). The development of alternative criteria on the basis of clinically measureable predictors of successful functional recovery is therefore considered a priority for the rehabilitation literature (Kruse et al., 2012).

Rehabilitation interventions are well represented in the ACL literature; there are a large number of RCTs, cohort and case control studies and within the last 10 years, 8 systematic reviews (Risberg et al., 2004; Smith et al., 2007, 2008; Andersson et al., 2009; Kim et al., 2010; van Grinsven et al., 2010; Kruse et al., 2012; Lobb et al., 2012) and 1 descriptive review (Manske et al., 2012). Whilst these reviews present the surgeon and rehabilitation professional with details of those rehabilitation interventions that are effective in enhancing recovery following ACLR, they do not provide the information on how those interventions are applied and adjusted within individual patients (van Grinsven et al., 2010; Kruse et al., 2012) or how they relate to criterion based systems. The evidence from systematic reviews will be presented followed by a discussion of criterion based rehabilitation programmes and the gaps in our understanding of functional milestones.

Details of the identified systematic reviews are displayed in Table 1. Recognised quality assessment tools are included in all reviews except Risberg et al. (2004) who used a customised tool with appropriate content. Appropriate databases, search terms, independent review and data extraction are used in all reviews. However, not all reviews performed well against the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guideline as evidenced by Lobb et al. (2012). Methodological quality of included studies is generally poor in both reviews performed by Smith et al. (2007, 2008). However the majority of studies identified by van Grinsven et al. (2010) have generally good quality according to the Cochrane tool; 23 were considered good, 10 questionable and 2 were excluded due to a poor rating. Common weaknesses in the available studies are highlighted by all the systematic reviews. These include a lack of justification for sample size, poor description of randomisation methods, compliance to rehabilitation is rarely measured and follow up is often too short (Risberg et al., 2004; Andersson et al., 2009; Kruse et al., 2012). There are also difficulties with definitions of several interventions (Johnson and Beynnon, 2012); in particular both accelerated rehabilitation and home based rehabilitation differ between study groups. The use of multiple outcome measures prevents the use of more powerful meta-analysis techniques. Johnson and Beynnon (2012) have highlighted these inadequacies in the current literature and proposed the development of standardised definitions for rehabilitation terms so that these issues might be addressed in future research. No more recent reference to this in the literature was identified.

Despite these inadequacies all authors make recommendations, often on the basis of strong or moderate evidence (Lobb et al., 2012). Neither bracing or continuous passive motion (CPM) are recommended immediately post-operatively (Smith et al., 2007, 2008; Lobb et al., 2012), however early weight bearing, range of movement (ROM) and muscle strengthening exercises are (Risberg et al., 2004; Andersson et al., 2009; van Grinsven et al., 2010; Kruse et al., 2012). Exercise therapy is supported using both strength and neuromuscular training incorporated in either home or clinic based rehabilitation programmes (Risberg et al., 2004; Kruse et al., 2012; Lobb et al., 2012). Strength training should include eccentric training (Andersson et al., 2009; Kruse et al., 2012) and both open and closed chain exercises for the quadriceps (Andersson et al., 2009; Lobb et al., 2012), although the range should be limited in the early phase to avoid excessive graft loading (Risberg et al., 2004). Neuromuscular training includes perturbation training (Fitzgerald et al., 2000; Hartigan et al., 2009) balance exercises, plyometrics, agility drills and sports or activity specific exercises (Risberg et al., 2004; 2007; Risberg and Holm, 2009). Neuromuscular electrical stimulation (NMES) to supplement quads strength in the early phase is also recommended (Risberg et al., 2004; van Grinsven et al., 2010; Kim et al., 2010).

Table 1: Appraisal of systematic reviews of rehabilitation following ACLR.

Paper	Studies	Level	Databases	Date	Reviewers	Bias	Topics	Recommended
Risberg et al., 2004	33	RCT's	PubMed, PEDro, SPORTDiscus, Cochrane	23	unknown	Own tool	Early WB Home based Strength training NMES NMT	Y Y Y Y Y
Smith et al., 2006	7	Clinical trials	AMED, British nursing, Cinahl, Cochrane, PEDro, PubMed,	2006	2	PEDro	Bracing	N
Smith et al., 2007	8	Clinical trials	AMED, British nursing, Cinahl, Cochrane, PEDro, PubMed	2006	2	PEDro	CPM	N
Wright and Fetzer, 2007	12	RCT's	PubMed, EMBASE Cochrane	2005	2	CONSORT	Bracing	N
Wright et al., 2008a	54	RCT's	PubMed, EMBASE, Cochrane	2005	unknown	Own	CPM Early WB Early ROM Bracing Home based	N Y Y N Y
Wright et al., 2008b		RCT's	PubMed, EMBASE, Cochrane	2005	unknown	Own	NMES	Y
Andersson et al., 2009	70	Level I and II RCT's	PubMed	2009	2	CONSORT	Bracing Home based OKC strength CKC Strength Eccentric Strength	N Y Y Y Y
Kim et al., 2010	8	RCT's	PubMed, CINAHL, SportDiscus, Web of Science, Cochrane	2008	2	PEDro	NMES	Y
Van Grinsven et al., 2010	32	Protocols RCT's Reviews	Cochrane, PubMed, EMBASE, PEDro	2006	3	Cochrane	Education Bracing Cryotherapy Early weight bearing Strength NMT	Y N Y Y Y Y
Kruse et al., 2012	29	Level I or II RCT's	Pubmed, Embase, Cochrane	2006 -10	3	CONSORT	Bracing CPM Early ROM NMT Eccentric Strengthening Home based	N N Y Y Y Y Y
Lobb et al., 2012	5	Systematic reviews	Medline, Amed, Embase, EBM reviews, PEDro, Scopus, Web of science	2011	2	PRISMA	Bracing CPM CKC strength OKC strength Home based	N N Y Y Y

Key: Y = yes, N = no,

Van Grinsven et al. (2010) adopted a very different style to reporting their systematic review that is consistent with the concept of criterion based rehabilitation. The findings of the quite rigorous systematic review are combined with both background theory and propositions from lower grades of evidence to fill in the gaps and create a time and criterion based rehabilitation schedule. Whilst there are some concerns that the lower grade evidence and expert clinical opinion will degrade the high level RCT evidence, this is also an important step to make the product useful and usable in the clinical environment. The findings and recommendations are no different from those in the other reviews, however the authors add context and this will be attractive to clinicians. It is however not always possible to identify where some of the recommendations have come from, particularly the phase based method that is presented and the basis for the criteria on which movement between phases is based. It is the definition of these criteria in relation to final outcomes that requires more attention.

The work of van Grinsven et al. (2010) shows a clear wish to develop criterion based rehabilitation. Initial developments in this process came from the Delaware group who published a programme still reliant on a temporal element, however clinical milestones defined the progression between phases (Manal et al., 1996). Milestones included ROM, knee outcome survey activities of daily living scale (KOS ADLS) scores, gait analysis, isokinetic strength and hop tests. The group have updated this guideline (Adams et al., 2012) in light of research developments. Evidence linking pre-operative function and post-operative outcomes (Spindler et al., 2011) has been used to give increased importance to pre-operative rehabilitation. Combined strengthening with the open and closed kinetic chain strengthening with the use of NMES is also recommended. The use of swelling and soreness rules to modify rehabilitation progressions and intensity are included as are progressive run programmes. The guideline is comprehensive; however recommendations for the objective criteria for rehabilitation progressions are not clearly linked to evidence of predictors of successful outcome. All functional testing remains based upon Limb Symmetry Indices (LSI), the potential flaws of which are discussed in detail in a later section considering appropriate comparators for defining outcome.

The return to sport (RTS) phase has attracted particular attention in terms of criterion based decision making (Mykleburst and Bahr, 2005, Kvist, 2005). Barber-Westin and Noyes (2011) published a systematic review of criteria used in the decision to return to full active participation following ACLR. Whilst the search is conducted across appropriate databases, the terms are quite limited raising the possibility that not all articles have been identified. However, a thorough search of the journals most likely to contain such articles is conducted and the number returned is in accordance with similarly time reviews of ACLR outcome studies (Letchford et al., 2012). There is no critical appraisal of the included studies, however this is discussed and is considered appropriate, since methodological quality will not impact upon the criteria that are proposed. The review findings suggest that time from injury is by far the most commonly used criterion. However, there is significant inconsistency with anything from 3 to 12 months suggested. Other criteria are less well established and infrequently reported; just 13% report using measurable objective criteria. These include; isokinetic muscle strength (9% of studies), clinical knee examination (6% of studies), dynamic function using hop testing (4% of studies), passive stability with arthrometer (1 study) and validated questionnaires KOS ADL (1 study).
Several models for criterion based RTS have been published and act as the current standard for decisions on RTS (Fitzgerald et al., 2000; Cascio et al., 2004; Kvist et al., 2004; Mykleburst and Bahr, 2005; Myer et al., 2006) Fitzgerald et al. (2000) criteria include LSI > 90% on isokinetic quads strength and a barrage of 4 hop tests (hop for distance, triple hop, triple swerve hop and 6m timed hop), >90% on KOS ADLS and the single assessment numerical evaluation (SANE). The work of Kvist (2004) provides a model in which all aspects of recovery are considered in the RTS decision. The model considers 3 primary criteria including rehabilitation, surgical and other factors; structure (passive stability: associated injuries) functional impairments (muscle strength; performance; ROM; effusion; pain; psychological factors) activity (functional stability testing) and social factors (work; family). These models again demonstrate the increasing influence of objective criteria being recommended for clinical decision making. Improving our understanding of functional recovery following ACLR and its relationship with other indicators of success is therefore further underlined.

In summary, there is systematic review evidence supporting the use of strength and neuromuscular training in rehabilitation following ACLR. Applying these in a criterion based framework seems to have become the adopted standard. Clinical milestones are used to guide progression and return to sport decisions. Currently, functional testing is recommended for this purpose; however there is little empirical evidence that current functional testing can predict future function or success following ACLR. Further investigation of the deficits and recovery of functional performance following ACLR and its relationship with success is required to inform the development of meaningful clinical milestones. The definition of success following ACLR is therefore important and will now be explored.

Defining success following ACLR and rehabilitation

Despite the development and validation of a broad selection of outcome measures specific to the ACL injured population and covering all three domains of the WHO ICF, there is still no gold standard definition for success after ACLR (Lynch et al., 2015). To date the literature has defined success primarily on the basis of three criteria; symptoms (Dunn et al., 2010), functional stability (Dunn et al., 2010; Barenius et al., 2014) and return to pre-injury participation (Fitzgerald et al., 2001; Dunn et al., 2010; Czuppon et al., 2013). In addition to these shorter term outcomes, a recent focus has considered a longer term view that includes the prevention of further injury to the meniscus and cartilage and limiting or preventing the early development of OA (Barenius et al., 2014; Culvenor et al., 2013). The Delaware-Oslo research group have recently published a consensus statement in an attempt to resolve this issue (Lynch et al., 2015). Criteria were identified from both literature review and expert opinion, piloted in a group of 40 specialists prior to a final survey being circulated internationally. In total, 1779 professionals from all continents and professional groups returned the survey. A dominance of physical therapists from North America and Europe may have implications for interpretation of this data. 80% of respondents were required to consider the criteria of primary or secondary importance, rather than "not important" or "do not use" in order to achieve consensus. Six criteria reached consensus; absence of giving way, quadriceps and hamstring strength LSI >90%, no more than mild knee effusion, return to sports and patient reported outcome measures (PROM). There was however no consensus on which PROM was most suitable. The knee outcome survey activities of daily living scale (KOS ADLS) and sports activities scale (SAS) had slightly higher summed importance, most likely reflecting the dominance of respondents from the USA. However none of the PROMs achieved consensus above 45% and all had consensus for being not important >32%. The Tegner and Marx were not considered important and most respondents were unfamiliar with them, which given the importance already assigned to return to sport and participation is a little concerning. This evidence for the inclusion of PROMs by clinicians seems to suggest that more work is required to get these validated tools accepted as useful measures of success following ACLR. The study also took the unusual step of defining thresholds for Tegner (7) and Marx (12) for satisfactory outcome. Given that not all subjects would have participated at this level prior to injury, this seems misguided and may again highlight the confusion amongst respondents about how return to sports or prior levels of participation is defined. Although functional testing did not meet the threshold, there was a summed importance of 75%, suggesting that a majority of respondents considered activity measures important; unfortunately there was no further exploration of this in the manuscript.

Several authors (Kocher et al., 2002; Swirtun et al., 2006; Heijne et al., 2008; Mancuso et al., 2001) have approached this topic from the patient's perspective. In a small but well executed qualitative study using semi structured interviews, Heijne et al. (2008 p325) reported that patients felt that ACLR was an opportunity to become "a completely restored functional human being" and that ACLR was the only choice if they wished to return to previous participation levels. Mancuso et al. (2001 p1009) found similar reports in a larger sample of ACLR patients who expected the knee to "be back to the way it was" and allow a return to pre-injury sports. Swirtun et al. (2006) studied 72 subjects following ACL injury, taking assessments of function (KOOS) and participation (Tegner), and crucially asking subjects about their decision to undergo surgery either early or later following a period of rehabilitation. The most frequent reason for early surgery (9 from 20) was disbelief that pre-injury activity could be performed without surgery. In the late reconstruction group recurrent instability (7 of 16) and inability to perform pre-injury activities (5 of 16) were most common reasons for pursuing surgery. Kocher et al. (2002) adopted a quantitative approach using correlation and regression methods to assess the relationship between clinical measures and patient satisfaction at mean 36 months following surgery. The study had a large sample (n = 201); however the follow up time varied considerably from 24 to 87 months from surgery. The patient satisfaction measure was a simple numerical rating scale (NRS) previously developed by the same research team and appropriately investigated for test retest reliability (ICC = 0.84) in a sample of 100 subjects. Structure variables (reduced ROM; passive instability; effusion; tenderness), symptoms with function (International knee documentation committee subjective knee form (IKDC SKF); Lysholm scale), difficulty with activities (walking; squatting; running; jumping) and reduced participation were all significant predictors of low patient satisfaction. The final regression model included seven variables (Lysholm; overall knee function score; ROM; tenderness; instability; effusion; flexion contracture) and predicted 83% of the satisfaction. There does appear to be a significant missing data issue which was managed by casewise deletion although the manuscript is not clear on this. Interestingly a fear of future knee impairment including OA was also cited by 4 subjects. In combination, this data strongly indicates that patients define success by normality and preinjury participation.

Therefore, it seems that there is agreement from both the clinician and patient perspective that restoration of pre-injury, healthy levels of knee function and participation is the definition of short term success after ACLR. This highlights the importance of defining healthy pre-injury status as the primary comparator and including all factors affected. These factors can be aligned to the WHO ICF model for health which will now be considered in the context of ACL injury.

Success in relation to the WHO ICF

The World Health Organisation international classification of functioning disability and health (WHO ICF, 2001) provides a conceptual framework within which to define and measure health. Its publication produced a radical shift in how health was conceptualised. By combining a traditional medical model which concentrated on the causes of ill health, with a social model which considered the impact of ill health on the ability to function in society, a holistic biopsychosocial approach to health and functioning was produced. The model describes human functioning on three levels; body (structure and function), person (activity) and society (participation) with the impact of both personal and environmental factors considered. Body structure refers to anatomical parts of the body, and function to physiological functioning of the body systems, with difficulties named impairments. Activity is defined as the person's ability to execute a task and is difficulties are called limitations. Participation is the ability of the individual to become involved in a life situation (WHO ICF, 2001), with difficulties named restrictions. Capacity and performance qualifiers are used to assess the impact of the environment. Capacity is assessment of an individual's capabilities within a standardised environment, whilst performance is observed within their own environment.

Several authors have utilised the ICF when discussing outcomes following ACL injury and ACLR (Zelle et al., 2005; Irrgang et al., 2008, Button et al., 2011). There has been some confusion in the literature with regards which domain of the ICF is being measured by certain popular outcome instruments, which is not assisted by coverage of multiple domains in some. Irrgang and Anderson (2002) provided a very useful scheme by which to differentiate this issue. Impairments may include pain, swelling, instability, muscle weakness and fatigue. Activity restrictions occur during tasks such as walking, running, jumping, landing and cutting. Participation restrictions occur in work, sports or recreational activities. An example of how this may apply in the ACL inured subject that has been adapted from descriptions by Irrgang and Andersson (2002) is presented in Table 2. This can be used to select outcomes from each domain of the ICF that will enable the definition of success described above. The selection of appropriate comparators for healthy, pre-injury status now requires exploration.

Table 2: Domains of the WHO ICF, items and measurement tools for the ACLD / ACLR population.

Domain		**Measurement tool**
Structure	Instability Swelling	KT 2000 Sweep test
Function	Range of motion Muscle weakness Symptoms such as pain, swelling, instability	Goniometer Isokinetics Patient reported outcome measures
Activity	Walking Hopping Squatting Running Jumping	Performance measures Strategy measures Biomechanics
Participation	Work Recreational activity Sport	Patient reported outcome measures

Appropriate comparators when assessing success following ACLR

It has been demonstrated that a return to pre-injury or healthy levels of function, activity and participation currently defines success after ACLR (Lynch et al., 2015; Heijne et al., 2008). Therefore it is logical to suggest that this must be the standard against which outcomes are compared. However this is the case for a majority of studies which report differences between cohorts, pre-post analysis in longitudinal data or compare outcome with predefined categories. These methods will be discussed in more detail before introducing clinical significance and healthy comparisons that are proposed as methods that will be able to appropriately assess outcomes against the currently accepted definition of success.

Many scoring systems devised to measure outcomes following ACLR (Collins et al., 2014) use systems to categorise subjects into groups using terms such as excellent, good or fair. Most of these categorisation systems were developed arbitrarily. More recent consideration of healthy normative values has put these categories into context. For instance, the Lysholm score was categorised as excellent (95-100), good (84-94) fair (65–84) and poor (<65).

However, data from healthy populations suggests that the mean values in healthy athletes is 99 with a range between 77 and 100 (Dermirdjian et al., 1998) and in the more general public, including subjects up to the age of 85, the mean is 94 (Briggs et al., 2009). This suggests that recovery defined as fair and good is always below average and that for the younger athletic population a fair outcome does in fact not represent recovery at all.
Another common methodology is pre-post analysis with inferential statistics used to provide a measure of the mean difference, the probability of this occurring by chance and therefore whether a hypothesis of no difference can be rejected (Jacobsen et al., 1991). Whilst this gives confidence that the change has occurred, statistically significant differences are often not equivalent to clinically meaningful changes and therefore more context is required. Various statistics including effect size, confidence intervals and minimal clinically important differences (MCID) aid in the interpretation by defining whether the magnitude of the change is sufficiently large to be considered meaningful to those affected by the condition (van Wijk, 2009; Page, 2014). However, even a change that is of known significance does not tell us whether the intervention has been successful (Jacobsen and Traux, 1991; Atkins et al., 2005). Clinical significance offers an alternative approach for defining recovery (Jacobsen and Traux, 1991; Atkins et al., 2005).
The approach was introduced in the psychology literature by Jacobsen et al. (1984), who started with the premise that expectations of therapy were most often to return to normal function. Successful therapy should therefore lead to an improvement beyond dysfunctional ranges and preferably to a range considered to be normal within society or equal to that prior to injury. Two measures are required to make this assessment. Firstly, whether the change is distinguishable from those occurring by chance or measurement error of the instruments and various reliable change indices have been proposed (Jacobsen et al., 19984; Atkins et al., 2005). The second is a method to categorise change from dysfunctional to functional ranges (Jacobsen and Traux, 1991) and whether individuals are indistinguishable from well-functioning individuals (Kendal et al., 1999). The original methods of Jacobsen and Traux (1991) have been adapted by several authors; however a recent simulation study has demonstrated that all methods lead to highly comparable classifications, particularly when highly reliable outcome measures are used (Atkins et al., 2005). The level at which normative comparison should be made is controversial. Whilst a large cohort of healthy normative values that provide matched comparisons on important

demographic parameters (age, gender, physical activity) are preferable (Turner et al., 2008; Fitzgerald, 2001), this data is not currently available for the primary outcomes of this study. A well matched healthy cohort will therefore need to be recruited for this purpose. Jacobsen et al. (1999) and Jacobsen and Traux (1991) have described cut off points for the categorisation of subjects at +/- 2 SD from the mean of the dysfunctional and functional groups when there is no overlap in the groups, or at a point defined by the reliable change index in overlapping groups. The work of Norman et al. (2003) suggests that meaningful change is most often described within half a SD of the mean. Unfortunately these methods have not been widely adopted in the ACLR literature; therefore outcomes in each of the domains will be discussed according to both statistical significance criteria and clinical significance criteria.

A similar discrepancy between statistical significance and clinical significance occurs in the literature regarding activity measures and functional performance tests. This arises as the contralateral limb is most often used as the comparator, with outcome represented as a limb symmetry index (LSI). Again seemingly arbitrary categories are applied to these indices to define acceptable levels of performance. Whilst this undoubtedly gives a measure of symmetrical performance, it does not necessarily provide a measure of normal performance. The hop tests are almost universally reported according to these symmetry values and will therefore form the basis for this discussion.

The LSI expresses performance (hop distance) of the injured limb as a percentage of the non-injured limb score. The rationale is that acceptable symmetry will limit overuse and injury risk when returning to participation in activities that carry an injury risk (Thomeé et al., 2011). However, the validity of LSI is reliant upon two assumptions; firstly that symmetry is a feature of the persons pre-injury functional status (i.e. healthy normality) and secondly that the non-injured limb represents that state of healthy normality and is unaffected by the contralateral injury (Bent, 2009; English et al., 2006; Fitzgerald et al., 2001). The literature is divided on this matter, with authors recommending (Petschnig et al., 1998; Logerstedt et al., 2012; Logerstedt et al., 2013) and cautioning against the use of LSI (Ageberg et al., 2002; Fitzgerald et al., 2001; Chmielewski, 2011; Thomeé et al., 2012) in favour of comparisons to healthy control values (Tegner et al., 1986; Ageberg et al., 1998;

Ageberg et al., 2001; Fitzgerald et al., 2001; English et al., 2006) or the use of absolute measures to add context to symmetry values (Reid et al., 2007).

Those that support LSI argue that the non-injured limb represents the healthy state (Logerstedt et al., 2013). However, in the papers reviewed only Petchnig et al. (1998) and O' Donnell et al. (2006) present data that attempts to confirms this in comparison to a healthy group. Although questionable matching is a weakness of both studies with the healthy subjects being relatively sedentary in comparison to the sample with ACL injury. Such a low activity level is likely to reduce physical performance and set the standard for performance at an extremely low level for the healthy leg. Van der Harst et al. (2007) have suggested that their evidence of no significant differences between the performances of limbs of healthy subjects can be used as justification for LSI and the normality of the uninjured leg. Whilst this data supports the first assumption on which LSI is based it does not provide evidence that the uninjured limb of ACLD subjects is unaffected and is therefore considered an invalid conclusion from the data.

There is however a growing body of evidence that impairments in the function of the contralateral limb exist following ACL injury. These include local physical changes and central nervous system adaptations that have been linked to motor control in the latter sections of this literature review (see dynamic knee stability section). There is convincing evidence for significant changes in muscle strength (Thomeé et al., 2012; Nyberg et al., 2006; Hiemstra et al., 2007; Neeter et al., 2006), muscle recruitment (Pfeizer and Banzer, 1999; Urbach, 2002; Chmielewski et al., 2004; Hart et al., 2010), proprioceptive awareness (Roberts et al., 2000, Friden et al., 2001; Solomonow and Krossgard 2001), reflex responses (Konishi et al., 2003 and 2007), balance reactions (Friden et al., 1989; Zatterstrom et al., 1994) and central processing of sensorimotor function (Valeriani et al., 1996; Ageberg et al., 2002; Courtney et al., 2005; Ageberg et al., 2009; Kaprelli et al., 2009) in the contralateral limb of ACL injured subjects. It seems logical to suggest that the sum of these impairments will result in reduced performance and altered strategies on the non-injured limb (Ingersoll et al., 2008).

If performance on the non-injured limb is affected, LSI would overestimate performance (Thomeé et al., 2012) and subjects who are classified as having acceptable symmetry may actually have reduced performance. In such a situation a subject with symmetrically poor performance is classified equivalent to a subject with symmetrically good performance. There are however few studies addressing performance of the non-injured limb in relation to healthy values, however there is data to suggest that performance is impaired. Button et al. (2005) demonstrated reduced hop performance in the non-injured limb early after ACL injury. Whilst no other studies making a direct comparison between the non-injured limb of ACLR and healthy subjects were identified, there is data available that supports this suggestion. Baltaci et al. (2012) identified no statistically significant difference (P>0.05) between the LSI for healthy (92%) and ACLR (95%) subjects and the authors concluded that function similar to that of healthy subjects is achieved. However the raw data shows that the ACLD have a SLHD mean distance of 133cm (+/-25) for the injured leg and 151cm +/- 25 for the non-injured leg, while the well matched healthy sample have a hop distance of 177 +/-12. The mean deficit in hop distance is therefore in the region of 25% and the ACLR group mean is well below 2SD from the healthy mean, which on clinical significance standards is a meaningful deficit. The small sample (n= 15) may contribute to a lack of power to detect differences; however the use of distance or symmetry seems to be the significant factor. There is also evidence of improving performance on both limbs in longitudinal data following ACLR (Logerstedt et al., 2013; Reid et al., 2007; Keays et al., 2000) and when ACLR is compared to ACLD (Gustavsson et al., 2006), suggesting that a bilateral deficit exists at baseline. This bilateral improvement also raises concern that bilateral performance gains may be masked when LSI is used as the only outcome measure. Reid et al. (2007) demonstrated significant changes in hop distance during a rehabilitation intervention, that were not apparent in the LSI values due to similar increases in performance on the contralateral limb. Keays et al. (2000) demonstrated a 5% increase in hop distance on the reconstructed limb, but LSI values remained the same (83%) due to a statistically significant 6% increase in hop distance on the contralateral limb. This is also evident in the data presented by Logerstedt et al. (2013) in a paper which exclusively reports LSI. Whilst the numerical data is not presented to support this suggestion, the graphical illustrations show a clear trend of increasing hop performance on both limbs throughout the course of this longitudinal study. It is suggested therefore that the LSI changes are highly likely to underestimate recovery.

Those who advocate use of the LSI have almost universally accepted a standard of 90% (Thomeé et al., 2011) to indicate recovery. The earliest suggestion for a cut off for acceptable performance was made by Barber et al. (1990) on the basis that 90% of healthy participants scored a LSI of > 85% and this has been gradually raised as data regarding healthy LSI has emerged. There is now strong evidence that healthy subjects are far more symmetrical than previously described with much higher LSI values for SLHD being reported; 94% (Ageberg et al.,1998), 95% (Petschnig et al., 1998), 95.5% (van der Hast, 2007) and 95.5% (Gokeler et al., 2010). This has led to more recent recommendations that LSI standards are increased to 90% (Logerstedt et al., 2012) 95% (Thomeé et al., 2011) and even 100% (Thomeé et al., 2011) in competitive athletes. Thomeé et al. (2012) has recently demonstrated the importance of standardising levels for LSI. Their LSI data with success defined at 80%, 85%, 90%, 95% and 100% clearly shows that the rising LSI cut off has dramatic effects on the number of subjects classified as recovered. At one year 64% were classified as recovered at 80% LSI whereas none reach 100% LSI. Thomeé et al. (2011) suggested that success rates at each level of limb symmetry should be published to show this fact. This does not however help with answering the question of what is a safe or appropriate LSI for defining recovery or recommending progression of rehabilitation interventions.

It seems clear that LSI needs more careful consideration as an outcome of rehabilitation research (Thomeé et al., 2012; English et al., 2006). The European Board of Sports Rehabilitation (EBSR) has recommended that absolute values and LSI should be presented both at group level and the proportion of subjects reaching each standard (Thomeé et al., 2011). The assertion of Logerstedt et al. (2013) that symmetry remains an important goal of post-operative rehabilitation is certainly valid and is in agreement with the concept of a return to health; however it also requires qualifying in the context of absolute performance. It will be important to gain further understanding of the performance of the non-injured limb in relation to healthy subjects in order to give context to LSI measures and make recommendations about their validity in different situations. Healthy comparison is an important consideration for defining success in the ACL injured population. In an early paper on the use of hop testing, Tegner et al. (1986) utilised clinical significance criteria, a return to this type of analysis may prove to be very useful. With success and appropriate measures and comparators defined, the review will now move on to discuss the current ability to predict success following ACLR.

Predicting success following ACLR

Predictors of outcome are central to the model for the development of novel solutions and interventions within orthopaedics proposed by Spindler and Dunn (2010). They propose an approach that utilises longitudinal studies to identify predictors of outcomes that are important to patients, before developing and testing solutions for implementation in the clinic. They make an important differentiation between modifiable and non-modifiable predictors. Non-modifiable predictors may influence choices with regards intervention pathways; for instance conservative or surgical management of ACL injury. Modifiable predictors can be used to develop new intervention strategies; for instance novel rehabilitation practices. Therefore, the identification of predictors that can be modified through rehabilitation interventions could inform practice and the development of new interventions to improve outcomes (Logerstedt et al., 2012; Thomeé et al., 2008). Recommendations that rehabilitation should follow a criterion based progression (Adams et al., 2012) based upon functional testing are now well established. However the measures of performance and movement quality that are so often used as rehabilitation milestones have not been well studied in terms of their appropriateness as modifiable predictors of successful outcome. A recent systematic review and meta-analysis from de Valk et al. (2013) summarises the current state of knowledge regarding predictors of outcome following ACLR. There is evidence that younger (<30) males with a lower BMI, higher pre-injury activity participation that are operated on prior to 3 months from injury have the best prognosis. Whilst meniscal injury, high BMI, reduced ROM and quadriceps strength were predictors of poor outcome. The absence of identified predictors potentially modifiable through rehabilitation is evident. The literature relating to predicting outcome in each domain of the ICF will be considered in the relevant sections later.

Section summary

ACLR and rehabilitation is a well recognised intervention for non-coping ACLD subjects, that aims to restore healthy or pre-injury levels of function, performance and participation. Whilst there is evidence of significant benefit from ACLR, outcomes are highly variable and currently applied methods often do not allow an assessment of recovery to healthy levels. Recovery of the highly symptomatic non-coping population is not well understood. Criterion based rehabilitation strategies are recommended, however the specific milestones are yet to be adequately defined in relation to predicting successful recovery. Therefore longitudinal studies with healthy comparisons are required to define deficits and recovery of functional performance and strategy that may act as modifiable predictors of success. These deficits relate to the theories of dynamic knee stability which will now be introduced and discussed.

Dynamic Knee Stability

Schipplien and Andriacchi (1991) were amongst the first to describe dynamic knee stability as a process of load sharing between passive and active stability mechanisms at the knee. Appropriate balance between these mechanisms promotes dynamic stability during functional tasks, inappropriate balance may lead to dynamic instability which may manifest as "giving way" of the joint. The passive system is defined by the mechanical limits of the joint surfaces and soft tissue restraints, which has been described by Blankevoort et al. (1998 p707) as "the envelope of passive stability". Both ACL (Corry and Webb, 2000) and meniscal injury (Ahn et al., 2011) may reduce passive restraint and increase the size of the envelope of passive stability as evidenced by clinically applied ligament stress tests (Kocher et al., 2004). The active system is defined by the application of load though weight bearing and co-ordinated muscle contraction, which provides stability through concavity-compression and mechanical restraint (Schipplien and Andriacchi, 1991; Lippitt et al., 1993; Kai-Nan, 2001). Importantly, the active system provides dynamic modulation of joint loading during functional tasks (Schipplien and Andriacchi, 1991; Williams et al., 2001) such that the envelope of dynamic stability is considerably smaller than the envelope of passive stability (Lippitt et al., 1993). The active stability mechanisms are therefore an important consideration in explaining deficits and recovery following both ACL injury and surgical reconstruction. This is clearly demonstrated in the variable amounts of dynamic instability and its apparently poor relationship to passive stability measures following ACL injury and reconstruction (Patel et al., 2003; Kocher et al., 2004). This variable response has led to clinical classification on the basis of dynamic stability, the presence of giving way during functional tasks being known as "functional instability".

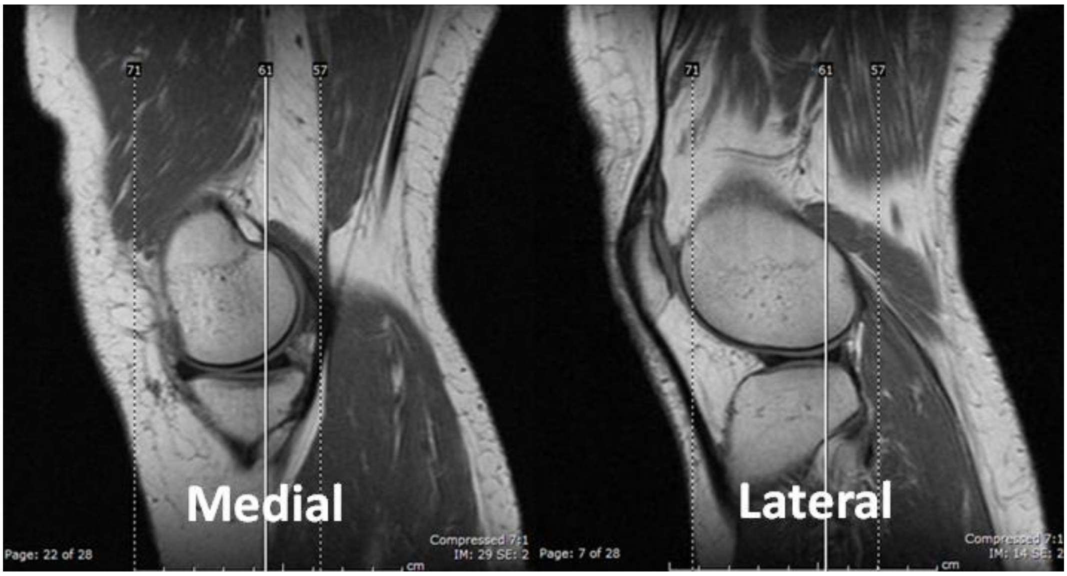
Noyes (1983) was the first to describe a classification of ACL injury on the basis of functional stability, which has subsequently been developed into the coper, adaptor and non-coper classification which has become engrained in the ACL literature (Snyder-Mackler et al., 1997, Rudolph et al., 1998). Copers are defined by their ability to return to full sporting participation without functional instability, adaptors change participation to maintain functional stability and non-copers experience functional instability and are either unable or unwilling to adapt (Noyes et al., 1983, Rudolph et al., 1998). Further exploration of this classification has confirmed that there is a poor relationship between passive and functional stability in ACLD subjects (Snyder-Mackler et al., 1997; Rudolph et al., 1998, 2000; Eastlack et al., 1999; Patel et al., 2003; Hurd et al., 2007). Furthermore, this remains the case after ACLR where functional outcomes are poorly related to passive laxity (Malcolm et al., 1985; Barrett et al., 1991; Harter et al., 1998; Seto et al., 1998; Hrubesch et al., 2000; Sernert et al., 1999, 2002; Higuchi et al., 2003, Kocher et al., 2004). Therefore, there is a need to look beyond simple mechanical models of passive instability and investigate the role of dynamic stability (Williams et al., 2001; Lui-Ambrose, 2003; Needle et al., 2014) and the sensorimotor system in producing co-ordinated motor control (Nyland et al., 1994; Solomonow and Krogsgaard, 2001; Riemann and Lephart, 2002a, 2002b) to maintain functional stability after ACL injury and reconstruction.

Dynamic knee stability was defined by Williams et al. (2001 p546) as "the ability of the knee joint to remain stable when subjected to the rapidly changing loads it withstands during activity". Many authors have contributed models which explain a variety of mechanisms by which dynamic stability is achieved (Schipplien and Andriacchi, 1991; Nyland et al., 1994; Solomonow and Krogsgaard, 2001; Williams et al., 2001; Kai-Nan, 2002; Reimann and Lephart, 2002a, 2002b; Wikstrom et al., 2006; Pietrosimone et al., 2012; Needle et al., 2014). All have drawn upon the growing biomechanical and neurophysiological literature and agree that there is a complex interaction between passive and active stability systems. The passive system refers to the anatomical structures that provide passive or mechanical stability to the joint; bony geometry, ligaments, joint capsule, cartilage and friction. The active system refers to the neurological and muscular (neuromuscular) systems that control movement and forces imposed upon the joint through both feedforward and feedback processes (Williams et al., 2001). Needle et al. (2014) used the term neuromechanical coupling to describe the interaction between the passive and active stability systems. They propose that individual capability to maintain neuromechanical coupling through adaptation and motor learning may explain the variable response to ligament injury (Needle et al., 2014). An appropriate neuromuscular adaptation would be capable of modifying the active stability system sufficiently to accommodate altered passive stability; neuromechanical coupling is maintained and the subject remains functionally stable during the task, i.e. they are a coper. However, if the adaptations are insufficient, the stability system becomes decoupled and the subject is functional unstable, i.e. a non-coper. Adaptation during tasks of different complexity may then explain the common strategy of reducing participation that occurs in those classified as adaptors. This model of neuromechanical coupling will form the theoretical basis for functional stability for this thesis. A brief introduction to the passive stability system as it is related to ACL injury will be provided before moving on to the active stability system and its response following ACL injury.

Passive stability system

The passive bony architecture of the knee (Figure 1) provides little stability, particularly on the lateral side, where the convex surfaces of the tibia and femur are inherently unstable (Williams et al., 2001). Stability is assisted by the menisci which act to deepen the tibial concavity and absorb compression through hoop stresses (Makris et al., 2011) in weight bearing. Conversely, the ligaments, capsule and musculotendinous tissues contribute significantly to the passive stability of the knee joint (Williams et al., 2001). Injury to these primary stabilisers is therefore a significant threat to functional stability of the knee. This is particularly true for the ACL which has a restraining effect over the more unstable lateral compartment (Amis et al., 2012). Injury to the ACL increases the envelope of passive stability (Blankevoort et al., 1988) reducing resistance to motion between the tibia and femur resulting in anterior and anterolateral instability (Hughston et al., 1976). The latter is characterised by the pivot shift phenomenon where the lateral tibial plateau is subluxed forward off the lateral femoral condyle and then relocated as tension develops in the lateral soft tissue during knee flexion (Bull et al., 1999 and 2002; Hoshino et al., 2007; Lopomo et al., 2010).

Figure 1: MRI of medial (Left) and lateral compartments (Right) of the knee showing the convexity of the lateral tibial plateau and the effect of the menisci increasing the concavity



Active stability system

In order to maintain a healthy knee, the neuromuscular system must work to constrain loads below the level at which the soft tissue restraints are excessively loaded (Williams et al., 2001). In that respect the neuromuscular control system becomes of particular interest in improving performance and preventing injury (Williams et al., 2001). After ACL injury the interest is in the potential to modify the neuromuscular system, through training and rehabilitation interventions, to a level which enables a subject to adapt to the deficiency in passive stability and regain functional stability (Williams et al., 2001; Riemann and Lephart, 2002a and 2002b). Neuromuscular control includes all the processes of unconscious activation of dynamic restraints in order to maintaining functional joint stability (Riemann and Lephart, 2002a). The common theme in the various dynamic stability models (Williams et al., 2001, Riemann and Lephart, 2002a) and one which is central to the neuromechanical coupling model (Needle et al., 2014) is the modulation of muscle stiffness.

Needle et al. (2014) suggest that the primary task of the active stability system is the regulation of muscle tone to optimise joint stiffness and facilitate a level of performance for a specific task. Muscle tone indicates a state of readiness of the muscle to act which can be modified according to the task and is therefore important for maximising performance and preventing injury (Needle et al., 2014). Stiffness can be viewed as a mechanism for injury prevention, with increasing tone leading to a stiffer joint and less chance of injury to the soft tissue restraints (Williams et al., 2001; Riemann and Lephart, 2002a). Equally, it is possible to suggest that following injury, enhanced muscular stiffness would be a method by which joint stiffness is modulated and functional knee stability augmented (Riemann and Lephart, 2002a). However, regulation of stiffness will be dependent upon the task and the required performance. By optimising stiffness, the tissues can be used to absorb, store and release elastic energy (Roberts and Azizi, 2011), improving efficiency and performance. Selective recruitment of muscle tone is therefore required to maintain a functional and dynamic performance envelope.

This selective recruitment is built into the feedforward or preparatory motor commands (Needle et al., 2014). The motor command is adapted so that an amount of variability in loading during a task is built into the movement pattern to account for any unforeseen or unanticipated events. Higher tone creates greater resistance to perturbations and an increase in fusimotor sensitivity which generates a quicker sensation of length change and reaction. Pre-activation is modified by several factors including anxiety, fear, uncertainty and attention, however most important of these are visual cues, experience and planning (Shumway-Cook and Woolacott, 2012). This reliance on experience is where the coupling between the passive and active stability systems is thought to occur through a process of motor learning (Needle et al., 2014). So, just as healthy individuals learn to control the envelope of stability of a joint during a novel task, so the ACLD subject can be considered to learn the control of the increased envelope of passive stability following injury (Williams et al., 2001; Riemann and Lephart, 2002a). Nyland et al. (1994) highlight this requirement for adaptation following ACL injury and that the compensations required to stabilise the injured knee may be seen as goals of rehabilitation, rather than normal movement. Similarly, adaptations which create mistimed or poorly planned muscular activation might impede performance and be a direct cause of functional instability. The concept of a negative feedback loop following ligament injury has been proposed by Wikstrom et al. (2013) to explain recurrent instability from this perspective of an inappropriate adaptation in neuromuscular control.

It is important to consider the mechanisms by which this selective muscle activation is controlled. Early theories considered regulation of muscle tone peripherally through the fusimotor system. An increase in activity within the gamma motor system shortens intrafusal fibres and increases the sensitivity of muscle spindles, resulting in an increased activity in the alpha motor neurone and increased resting tone in the muscle (Needle et al., 2014). However, the fusimotor system is also under descending inhibitory influence from higher centres of the central nervous system (CNS). Much of the understanding has come from subjects with damage to the CNS and little is known about these mechanisms in healthy athletic subjects, however recent evidence is available linking cortical measures and joint stiffness (Needle et al., 2014). However, in states of anxiety and stress, reductions in cortical inhibition increases muscle tone and leaves a state of readiness in the system, allowing an individual to respond more quickly (Davis et al., 2011; Needle et al., 2014, Hodges and Tucker, 2011). However, if excessive this also disrupts normal agonist co-contraction and leads to erratic movements, reduced performance and functional instability (Swanik et al., 2007).

Using the model of neuromechanical coupling (Needle et al., 2014) it is therefore argued that functional instability represents a failure of the motor control system to appropriately regulate muscle stiffness during a task (Needle et al., 2014; Williams et al., 2001; Riemann and Lephart, 2002a). ACL injury is therefore considered a neuromechanical injury that requires neuromechanical adaptations to affect recovery (Valeriana et al., 1999; Baumeister et al., 2008; Benjaminse et al., 2015). Consideration is now given to impairments to the sensorimotor system following ACL injury that may impair these neuromechanical adaptations.

Impairments of sensorimotor function following ACL injury

Whilst the impairment in the passive stability system is quite obvious and simple to measure in the clinical environment (Malanga et al., 2003; Leitze et al., 2005; Kostogiannis et al., 2008; Queale et al., 1994), there are also impairments of the active stability system which require consideration. Many basic science studies have assessed the response of the neuromuscular system to joint injury (Hurley, 1997), theoretical frameworks have been proposed (Pietrosimone et al., 2012) and the literature of relevance to consequences of ACL injury documented in review papers (Ingersoll et al., 2008; Ageberg et al., 2002). Unfortunately, both of these reviews are descriptive, neither are systematic in the methods to identify and select the data they present and risk of bias and poor quality of data cannot be assessed. Both do however contain extensive, relevant and up to date reference lists. Both consider proprioception, central mechanisms and muscular function which will now be considered.

Proprioception

Motor control patterns are under constant review by the CNS, adapting to the integration and processing of sensory input, efferent commands and resultant movements (Reimann and Lephart; 2002b). Proprioceptive information plays an integral role in the development and modification of internal models used within feedforward motor control (Reimann and Lephart, 2002b) and is believed to be an important factor in recovery following ACLD and ACLR. The ACL is a sensory organ, containing high volumes of Golgi tendon organs particularly at the distal attachment sites (Schultz et al., 1984; Zimny et al., 1986; Shultz et al., 1987). Disruption of the ligament has been suggested to limit the sensory afferent information supplied to the CNS and to be responsible for the proprioceptive deficits that have been identified (Ageberg, 2002). More recently preservation of the ACL stump and incorporation into the ACLR has been proposed as a method of retaining some of this afferent input (Ahn et al., 2011; Dhillon et al., 2010). However, these deafferentation theories should have limited impact on proprioception as ligament receptors are known to act predominantly as end range sensors (Proske and Gandevia, 2009). Johansson et al. (1991) proposed the final common input theory, which suggested the deafferentation caused by ACL transaction interferes with gamma loop function and inhibits muscle tone and sensory information passed upwards to the CNS. These processes are further inhibited by the neurophysiological response to inflammation, pain and swelling within the joint (Torry et al., 2000; Hodges et al., 2009).

The modern view considers the muscle spindles as the principle kinaesthetic receptors with additional contributions made by receptors in the skin (Proske and Gandevia, 2012). When considering the sensation of force and heaviness then the Golgi tendon organs provide a valuable contribution (Proske and Gandevia, 2009). There is considerable evidence that supports this proposition, including studies on joint replacement and ligament reconstruction, dorsal column lesions, the thixotrophic properties of muscle and the use of muscle vibration (Proske and Gandevia, 2009 and 2012). These studies are very well summarised in an extensive narrative literature review from Proske and Gandevia (2012) which represents the state of the art in neurophysiological research. Whilst there is considerable evidence that joint receptors should be considered only as detectors of end range stress, there is also evidence that when these receptors are blocked the proprioceptive sense is diminished. It seems therefore that joint receptors do influence the output and interpretation of muscle spindle data. This is in agreement with the final common input theory proposed by Johansson et al., (1991) to explain how deafferentation caused by ACL transaction may feed into alterations in fusimotor function and the final sensory output to the CNS.

CNS changes following ACL injury

ACL injury has been proposed as a deafferentation injury of the CNS by Kaprelli and Athanasopoulos (2006). They propose that the loss of mechanoreceptors in the ACL and the associated neurophysiological response to inflammation, pain and swelling leads to plastic adaptation within the CNS. Several studies have investigated CNS activity in ACLD and ALCR subjects using different technologies, including functional magnetic resonance imaging (fMRI), electroencephalography (EEG) and somatosensory evoked potentials (SEPs). The earliest of these studies used SEP's to measure the CNS response in ACL injured subjects compared to healthy individuals during gait. Changes in SEP's were identified in the ACLD subjects and were postulated to be a sign of CNS reorganisation (Valeriani et al., 1996, 1999). More recently Courtney et al. (2005) have updated and expanded these studies to include functional measures and ACLD subjects of varying functional capabilities. Again, altered SEP's were identified in conjunction with alterations in neuromuscular control. However these changes were only apparent in high functioning ACLD copers and not in poor functioning non-copers. They suggested that the altered SEP's and motor output therefore represent a successful compensatory strategy for ACLD.

In a later study Kaprelli et al. (2009) used fMRI to measure brain activity in ACLD subjects during a simple knee flexion task. They identified reorganisation of the CNS with reduced activity in some somatosensory areas and increased activity in motor areas associated with conscious control and planning (presupplementary motor area, posterior secondary somatosensory area, and posterior inferior temporal gyrus). These findings indicate the apparent need for increased attention and planning for movement in ACLD subjects.

Two further studies from Baumeister et al. (2008; 2011) measured EEG during a force matching task in ACLR and healthy subjects. Whilst there was no significant difference in performance between groups, EEG identified significant differences in CNS activity. The ACLR subjects demonstrated increased activity in the frontal theta, an area which has been associated with working memory, information processing and attention in cognitive and sensorimotor tasks and specifically involved in target selection, error detection and performance monitoring. This may reflect a higher focus of attention and therefore higher neurocognitive resources related to this task in the ACLR subjects.
In combination, this provides evidence for plastic adaptation of the central nervous system in ACL injured and reconstructed individuals. The areas that have been highlighted are involved in the planning and cognitive control of movement, suggesting alterations to the motor command and increase in the cognitive load for these subjects. This supports increased uncertainty in movement control and an adapted central command attempting to control it. This would support proposals for rehabilitation strategies in line with motor learning principles to promote reorganisation of the CNS (Benjaminse et al., 2015).

Muscle function

Muscle function is known to be impaired in the ACLD and ACLR population and to take considerable time to recover (Peterson et al., 2014). Whilst the effects of reduced use following injury are likely to be significant, several neurological mechanisms underlying this deficit have also been proposed and investigated. This section will discuss the response of the muscle to reduced use before considering the neuromuscular causes of altered muscle function.

Muscle tissue is perhaps one of the most plastic tissues in the human body, with a capacity to adapt to increased and reduced use (Leiber, 2010). Leiber (2010) summarises the effect of reduced muscle use in three processes; atrophy, reduction in force generating capacity and a slow to fast fibre type conversion. The magnitude of these processes is directly related to the change in use of the muscle which means that the often used postural control muscles are more affected than the less often used mobilising muscles (Leiber, 2010). This reduction in slow postural muscle and increase in fast postural muscle fibre type is suggested to result in altered neuromuscular control and is likely to be linked to the process of muscle dyskinesia described later. Importantly, models explaining the effects of increased use on muscle tissue report the opposite effects to reduced use and therefore this process is seemingly fully reversible by a process of increased use (Leiber, 2010). Whilst the current evidence suggests that changes with increased use occur more slowly than with decreased use there are no studies that have enabled this to be quantified (Leiber, 2010). Whilst this suggests that rehabilitation has an important role in increasing use to facilitate muscle plasticity, it is not possible to be confident of the most appropriate methods or the extent of recovery of muscle morphology.

Motor output is also modified by the processing of afferent information within the CNS. As already described ACL injury impairs this process and muscle function is altered through a variety of mechanisms that have been collectively described as arthrogenic muscle inhibition (AMI). A useful model explaining the mechanisms of AMI has been created by Rice and McNair (2010) on the basis of a comprehensive search and narrative review of the literature. Factors affecting the output at the alpha motor neurone are split into three sections; those affecting sensory output from the knee (e.g., inflammation, pain, swelling, receptor damage and instability), supraspinal influences (e.g. reduced voluntary effort), and the spinal reflex pathways (gamma) that modulate these factors and directly stimulate the alpha motor neurone.

A well conducted systematic review and meta-analysis from Hart et al. (2010) demonstrated that AMI of the quadriceps was present in up to 100% of ACLD patients and 71% of ACLR subjects, supporting previous suggestions that AMI is reduced but often not resolved following ACLR (Urbach et al., 2001). The amount of AMI has also been demonstrated to be proportional to the extent of joint injury, with isolated ACL injured subjects demonstrating lower AMI than those with concomitant injuries (Urbach and Awiszus, 2001). Importantly the effect of AMI has been observed bilaterally after ACL injury and surgery (Urbach et al., 2001; Chmielewski et al., 2004; Hart et al., 2010), whilst the effect is less severe than on the injured limb it remains significantly different from healthy levels (Rice and McNair, 2010). Whilst AMI is evident acutely following injury, Krishnan and Williams (2011) have demonstrated that activation and inhibition measures had a small effect in their sample of ACLR subjects who were between 2 and 15 years from surgery. They concluded that peripheral muscle changes were therefore primarily responsible for the weakness that they identified.

Recent investigations of muscle function following ACL injury (Williams et al., 2003; 2004, 2005; Bryant et al., 2009; 2010; Macleod et al., 2013; Teliandis et al., 2014) have identified changes in the selective recruitment of motor units within the quadriceps and hamstring muscles, that has been named muscle dyskinesia. The earlier studies of Williams et al. (2003, 2004, 2005) measured the specificity of EMG data during a target matching protocol for isometric contractions. The data confirmed that ACLD subjects had less specific muscle activation than either the non-injured or healthy comparator subjects. The most striking feature was the maintenance of quadriceps activity in all tasks, including those where the quadriceps are usually inactive. The authors describe an apparent inability to switch off the quadriceps when not required (Williams et al., 2003, 2004) and that this co-contraction is proposed as a method by which joint stiffness is increased in ACLD subjects. More recently the study has been repeated, comparing coper and non-coper ACLD subjects (McLeod et al., 2013). Whilst the non-coping ACLD subjects displayed the same significant differences in activation from the healthy group, coping ACLD subjects did not. This led the authors to propose that the reduced selectivity of muscle activation may be a feature of non-coping and functional instability. The more recent investigations have used sub-maximal contractions near full extension and identified similar inability for ACLR subjects to control quadriceps and hamstring force output (Teliandis et al., 2014). Similar studies using experimental pain (Mellor and Hodges, 2005; Hodges et al., 2009; Tucker and Hodges, 2009; Tucker and Hodges, 2010) have identified similar muscular dyskinesia that is highly variable and spread both within and between muscles. These studies demonstrate that the neuromuscular system adapts to instability and pain by altering the recruitment patterns of motor units within and between individual muscles and muscle groups. Studies like these have been used in the formulation of a new theory of motor adaptation to pain from Hodges and Tucker (2011). This and other theories of movement adaptation following injury will now be considered.

Models of movement adaptation following injury

ACL injury has been established as a neuromechanical injury affecting both active and passive stability systems. This section will consider three models of neuromuscular adaptation following injury, from the pain (Hodges and Tucker, 2011), motor control

(Shumway-Cook and Woolacott, 2012) and motor learning (Bernstein, 1967; Fitts and Posner, 1967; Benjaminse et al., 2015) literature that may each provide insight into interpretation of movement adaptations following ACL injury and reconstruction and their implications for rehabilitation.

Pain and motor control

The theories of vicious cycle (Roland, 1986) and pain adaptation (Lund et al., 1991) have been used within rehabilitation practice to explain predictable and patterned responses of muscle to pain. Hodges and Tucker (2011) have highlighted that a growing amount of the neurophysiological literature reports motor responses that vary within and between muscles and tasks, and suggest that these theories are over simplistic. They propose an alternative model where responses to pain are not stereotypical. The basic premise is that adaptations aim to protect from pain, further injury or the threat of pain and injury (Hodges and Tucker, 2011). Muscle activity is redistributed within and between muscles in order to change the mechanical behaviour and modify movement (Hodges, 2010). These changes occur at multiple levels of the motor system and may be complementary, additive or competitive (Hodges, 2010). The resulting motor pattern is of short term benefit, however there is potential for long term consequences due to modified load, decreased movement and decreased variability (Hodges and Tucker, 2011). For instance, redistribution of activity within a muscle may alter the distribution and direction of force production, reducing load on painful structures within the muscle or the movement. Such changes have been demonstrated in the vasti in response to experimental pain (Mellor and Hodges, 2005; Hodges et al., 2009) with resulting changes in the force output (Tucker and Hodges, 2010). The result of change in the activity of individual muscles results in increased stiffness to control displacement and damping to reduce velocity (Hodges and Tucker, 2011). Whilst the gross features of the task are maintained, quality is affected and should therefore be a target for rehabilitation.

Importantly in this model the resolution of pain does not necessarily give a stimulus to return to the original movement or muscle activation pattern (Hodges and Tucker, 2011). If this were to be transferred to the variety of symptoms of ACLD including pain and instability, the question would arise whether the restoration of passive stability is sufficient stimulus to trigger a return to normal muscle activity, or whether a further stimulus (rehabilitation) is required to facilitate adaptation in the direction of recovery? The multiple possible solutions that are demonstrated by high variability in biomechanical measures, may in some way relate to clinical sub groupings that have been developed (Hodges and Tucker, 2011). Individual variance may suggest a search for a less painful movement option which would fit with motor learning theories of variable practice and allowing individuals to experiment and identify an appropriate strategy on the basis of feedback and experience of results and performance. The rehabilitation goal is to modify the adaptation and therefore this needs to be done on an individual level and requires interventions that target higher levels of the motor system. Motor learning strategies might therefore be used to adapt unhelpful movement strategies and for the learning or relearning of more helpful strategies. These are all dependant on conscious and precise correction of movement and muscle activity; rehabilitation therefore requires conscious attention to change cortical representation.

A motor learning perspective

It has been suggested that ACL injury presents a novel challenge to the motor control system and therefore a motor learning perspective will be required. Not only is there the challenge of controlling functional knee stability in the presence of an increase in the envelope of passive stability, but also in the presence of the associated impairments of the sensorimotor system.

There are two complementary and well established models of motor learning that will be considered. Each utilise a three stage model, however each emphasises different important concepts of cognition and biomechanical control during motor learning. Fits and Posner (1967) suggested that motor learning starts with a cognitive phase where internal cues and feedback are used to select strategies that accomplish the task, a second associative phase refines these strategies to improve consistency and a final stage represents autonomous performance requiring low levels of attention. Bernstein (1967) developed a similar model using the terms novice, advanced and expert to describe these performance stages. Importantly, Bernstein (1967) considered these three stages in biomechanical terms, suggesting that novice performance was characterised by restricting degrees of freedom and that as competence increases degrees of freedom are gradually released to produce a finer, more complex and more efficient movement.

The underlying principles of motor learning that come from such models are frequently considered in rehabilitation, particularly in the way that tasks or exercises are taught and practiced. Simple tasks are performed using internal cues that are gradually removed as the task becomes more autonomous. Importantly, recent evidence is demonstrating that external cues are far more useful in guiding motor learning processes, resulting in recommendations for a move from internal cues to external cues in rehabilitation interventions (Benjaminse et al., 2015).

The novelty of the tasks that are selected will be important considerations from a motor learning perspective. Walking gait is a well practiced motion in which all subjects would be considered experts with vast experience in different environments and after different perturbations. The rehabilitation of walking gait under the new circumstances caused by ACL deficiency can therefore draw on that vast experience. However if tasks are selected which are novel the process of motor learning is more challenging (Benjaminse et al., 2015). Clinical tests such as hop for distance may be considered to relate to sporting activity, however hops are rarely practiced and there are unlikely to be many who would be able to call themselves expert in it. The experience on which to base adaptation for these novel tasks is therefore less and the motor learning is therefore more challenging. The selection of well practiced and novel tasks in rehabilitation will therefore influence the process of motor learning, modifying tasks to individuals past experience is therefore important to promote restoration of previous skills (Benjaminse et al., 2015; Wolpert et al., 2011).

A task oriented model for motor control

Shumway-Cook and Woolacott (2012) have written extensively on motor control from the perspective of neurological conditions; however this work also translates to musculoskeletal injury. Their model of task oriented rehabilitation divides movement on the basis of task, individual and environment, the interaction between these three factors producing the resulting movement, and importantly adaptation of each being capable of changing the movement pattern. The capability of the individual to meet task and environmental demands will define success in completing the task and the manner (strategy) in which it is done (Shumway-Cook and Woolacott, 2012). A complex task will be difficult to achieve for an individual with limited capabilities, whilst a simple task will be completed with ease. However, it is possible that complex tasks may be completed despite limited capabilities, by the use of compensation in the strategy. So the strategy relates the demand of the task to the abilities; when poor strategies are used for difficult tasks they may fail; if strategies are inefficient we may pass simpler tasks but not more complex ones (Shumway-Cook and Woolacott, 2012).

In this model recovery is defined as “the returning capability of the individual to perform a task using the mechanisms previously used”, Shumway-Cook and Woolacott (2012 p39). However, if an alternative strategy is adopted the movement is considered compensated. Whilst compensatory strategies may be successful in achieving a level of functional performance they may also lead to deleterious effects. There is evidence that ACLD subjects develop compensatory movement strategies in an attempt to maintain performance (Ernst et al., 2000; Oritz et al., 2007; Oberlander et al., 2012); that these strategies can persist following ACLR (Gokeler et al., 2013; Gokeler et al., 2010; Oberlander et al., 2013); and are proposed to be a contributor to the early development of degenerative changes seen in this population (Andriachhi et al., 2009). The standard seems to be set to work towards normal movement strategies within musculoskeletal rehabilitation, both for short term performance and long term health. However, at what point a compensatory strategy becomes acceptable and to what extent it will be the cause of longer term degenerative disease has yet to be fully defined. The question therefore is whether normal strategy is important or whether compensated strategies that achieve performance should be preferred. The development of instruments to identify these strategies during rehabilitation is required as a first step in unpicking these debates (Fitzgerald et al., 2001; Gokeler et al., 2010; Augustsson et al., 2006; Engelen-van Melick et al., 2013).

The concept of compensation is also presented within the clinical rehabilitation literature; Elphinstone (2008) presents this concept simply as an equation to be balanced. When the ability to compensate is greater than the functional loading the system is trainable and adapts. However, when the ability to compensate is less than the functional loading the system becomes impaired. Using this concept it could be proposed that coper’s maintain a trainable system after ACL injury and can progress functional loading and return to prior activities. However, non-coping subjects have an impaired system which requires intervention to facilitate appropriate compensations and modifications to functional loads. During rehabilitation, the ability to compensate must be matched to functional loading and progressed appropriately in order to facilitate and maintain a trainable system and achieve recovery. It is suggested that the individual's ability to compensate is defined by effective coupling of the neuromechanical (Needle et al., 2014) stability systems. Importantly, functional loading is task dependant and therefore requires a discussion of task complexity.

Task complexity

Taxonomies of task complexity are often developed by therapists on the basis of applied knowledge and clinical wisdom. There are examples in the literature where taxonomies have been built upon sound biomechanical principles where task demands are determined through combinations of joint excursion, moments, and motor control (Button et al., 2014; Ingersoll et al., 2008; Ernst et al., 2000; Banzer et al., 1999). In the ACL injured population, task demand is most often considered in terms of the challenge to functional stability. It is assumed that subjects will be able to perform better in tasks that are less challenging and will be unable or perform poorly in more complex tasks. Several authors have highlighted such taxonomies. Ingersoll et al. (2008) described abnormalities becoming exaggerated as tasks become more complex, they highlight evidence that gait abnormalities are relatively subtle, but become exaggerated in jogging, running and jumping. Ernst et al. (2000) demonstrated greater differences in kinetics and kinematics in ACLD subjects when landing from a jump was compared to take off. The increased complexity of attenuation of forces during landing in comparison to production of force in take-off was proposed as the mechanism for this. Banzer et al. (1999) studied three functional test and found adaptation to kinematics and kinetics in hop but not stair ascent, suggesting the former was more complex and therefore more likely to require adaptation within that sample to perform. Button et al. (2014) have used biomechanical analysis to demonstrate the progressive complexity of gait, bilateral squat and hop. They demonstrated that hop landing had the greatest knee moments and that moments during squat were greater than in gait.

An alternative model would be to explore the deficits in activity parameters within the injured or recovering population and use these deficits to define complexity of task. Hopper et al. (2008) did just this, studying hop tests after ACLR and identified that the hop tests recovered sequentially across time starting with the 6 m timed hop, stair hop, vertical hop and finally the cross over hop tests. This suggests a hierarchy of test complexity for the ACLR population. More recently Risberg et al. (2009) report that rehabilitation was effective in changing joint loads in walking but not hopping, suggesting that the latter is a more advanced task for this group of subjects.

There are however also studies which contest common thinking on the complexity of tasks and that may illustrate the different challenges to the capabilities of ACLD and ACLR subjects. In the work of the Delaware group, Fitzgerald et al. (2000) demonstrated that of four hop tests (hop for distance; triple hop for distance; triple cross over hop; 6m timed hop) deficits in the 6 m timed hop were more pronounced between successful and unsuccessful ACLD subjects returning to pre-injury activity. This test is often considered the simplest (Fitzgerald et al., 2000; 2001) of the four tested, however in this situation it appears more complex. This suggests that lower load repetitive tasks may be more complex than higher load discrete tasks and further investigation of this is required. It is also important to consider that task complexity is dependent on the individual. For instance, variable impairment of the active and passive stability systems may make tasks variably difficult within sub groupings of ACLD subjects. Equally, the challenge of controlling an ACLD knee is different from that of an ACLR knee and therefore task complexity and adaptations required may vary before and after ACLR. This suggests that the rehabilitation strategy needs to be individualised and may explain some of the unexpected findings in task hierarchies.

For the purpose of this study, three theoretically hierarchical tasks were selected. The literature presented above agrees that walking gait is a simple task and hop for distance a complex task (Banzer et al., 1999; Kocher et al., 2002; Risberg et al., 2009; Ingersoll et al., 2008; Button et al., 2014) frequently used in the ACLD and ACLR population. Whilst squatting is known to be intermediate (Button et al, 2014) on many grounds, it was considered too close to gait and therefore a progression to a single leg squat with multiple repetitions was selected as a proposed intermediate task to test the idea that continuous tasks are more complex. The biomechanical evidence presented above and basic principles of task progression from motor control and learning perspectives (Shumway-Cook and Woolacott, 2012) were used to justify this proposed hierarchy. The elements of interest in exercise progression within the rehabilitation environment are detailed in Table 3, which acts as the template for task hierarchy for this study.

Table 3: Proposed task hierarchy from biomechanical and motor control perspectives.

	Walking	**Single leg squat**	**Hop for distance**
Frequency of use	High	Low	Low
Knee moments	Low	Moderate	High
Control	Continuous	Continuous	Discrete
Base of support	Mobile	Stable	Mobile
Speed	Slow	Slow	Fast
Acceleration	Small	Small	Large
Range on Motion	Small	Large	Medium

Key: Items in green are considered simple, yellow intermediate and red complex. Hierarchy compiled using data from Banzer et al. (1999), Kocher et al. (2002), Risberg et al. (2009), Ingersoll et al. (2008) and Button et al. (2014).

Section summary

The theories of dynamic stability offer an explanation for the variable response to ACL injury and reconstruction. Non-coping is explained by neuromechanical decoupling. Variable resolution of impairments and ability to re-couple the stability systems through motor learning can explain variable recovery and coping. The identification of protective strategies that promote performance and minimise long term consequences seems to be a viable aim of rehabilitation that might be facilitated by utilising task oriented approaches to motor control and motor learning rehabilitation strategies. A greater understanding of the deficits and recovery of performance and strategy during common functional tasks is required to enable this progression rehabilitation.

Deficits and recovery in each domain of the WHO ICF.

The final section of the review considers each domain of the WHO ICF; how they are measured, healthy values, deficits in ACLD, recovery and modifiable predictors of outcome following ACLR subjects.

Structure

Passive instability is perhaps the most obvious measure of structure in the ACL injured knee and has been considered an important outcome (Irrgang et al., 2008). Anterior laxity can be reliably assessed both manually using the Lachmans test (Malanga et al., 2003) and using instrumented methods such as the KT2000 (Queale et al., 1994). However this uniplane instability rarely correlates to functional instability (Strand et al., 2005; Leitze et al., 2005) and is therefore of limited value. In contrast, the pivot shift test is a measure of anterolateral rotator instability (Malanga et al., 2003) and has been shown to be more highly correlated to both functional instability (Leitze et al., 2005; Kostogiannis et al., 2008) and long term knee function (Jonsson et al., 2004).

The meniscus is commonly injured, either at the time of ACL injury or in the period following. Table 4 summarises published data and demonstrates the large variance in the proportions that are reported. Jones et al. (2003) performed a well conducted narrative review and found that the incidence ranged from 16 to 82% in acutely ACL injured knees and was as high as 96% in chronic ACL injured knees. Despite differences in the measurement of meniscal injuries, many authors have reported greater numbers of meniscal injuries, particularly medially, with increasing time from injury (Murrell et al., 2001; Church et al., 2005; O'Connor et al., 2005; Papastergiou et al., 2007; Tandogan et al., 2004; Granan et al., 2009; Slauterbeck et al., 2009; Barenius et al., 2014). This suggests that these injuries are acquired, most likely as a result of the posterior horn's significant contribution to stability of the ACLD knee (Ahn et al., 2011; Markolf et al., 2012). Three studies have made a significant contribution to confirming the acquired nature of these injuries. Tayton et al. (2009) demonstrated an increase in the number of meniscal injuries between initial MRI diagnosis and ACLR following failed conservative interventions. The initial diagnosis was mostly completed with MRI and final diagnosis at arthroscopy. Although these methods are known to have some variance (Crawford et al., 2007) this is not sufficient to explain the differences observed. Yoo et al. (2009) avoid this limitation by using repeat MRI to assess for changes in menisci between initial diagnosis and time of surgery. Although the sample is small the changes are significant. In a large and well conducted retrospective study Slauterbeck et al. (2009) demonstrated a clear increase in meniscal and chondral injury frequency and severity with increasing time to surgery. Whilst the suggestion that ACLR would prevent these injuries by stabilising the knee seems to be logical, no strong evidence to support this effect was found. On the basis of the frequency data described, several authors have made recommendations for the timing of ACLR to avoid acquired meniscal injuries, however they are contrasting; 3 months (Papastergiou et al., 2007; Slauterbeck et al., 2009), 6 months (O'Conner et al., 2005) and 1 year (Tandogan et al., 2004) have all been proposed.

Table 4: Studies reporting incidence of meniscal injury associated with ACL injury

Study	n	Meniscus affected		
		Any	Medial	Lateral
Yoon et al., 2011	81		54%	51%
Borchers et al., 2011	508		40%	46%
Murrell et al., 2001	130	72%		
Yoo et al., 2009	31	84%		
Granan et al., 2009	3475	47%		
Smith and Barrett, 2001	1065		53%	47%

Key: n = number of subjects

The treatment of meniscal injury at ACLR varies. Noyes and Barber Westin (2012) have performed a good quality systematic review and identified that resection remains the most common treatment of meniscal injury in the ACLD knee undergoing reconstruction occurring in 65% of knees and repair in about one third. Whilst some authors have attempted to synthesise the literature regarding when to resect, repair or leave alone (Pujol and Beaufils, 2009) there remains no agreed evidence based consensus. Meniscal injury has been associated with poor functional outcome at two (Ross et al., 2002), three (Ross et al., 2010), five (Magnussen and Spindler, 2011) and six years (Spindler et al., 2011) following

ACLR and is also considered one of the greatest risks for the early development of OA in the ACL injured knees (Lohmander et al., 2007; Oiestad et al., 2009; Keays et al., 2010; Murray et al., 2012; Louboutin et al., 2012; Magnussen et al., 2013). Meniscal injury and intervention will therefore be of interest in terms of functional recovery and long term knee health.

Knee Function

Knee function was described earlier by an array of signs and symptoms including functional instability, pain, swelling, locking and ROM restrictions (Irrgang and Andersson; 2002). Knee function is generally measured through the use of PROMs. Throughout the 1990's there was an explosion of PROMs entering the published literature, which has limited the ability to synthesise data across different studies. This point was highlighted by Risberg et al. (1999) who identified 38 different scoring scales in 52 articles published in two of the most prominent journals for knee injury research (Journal of bone and joint surgery and American journal of sports medicine). Two years later Johnson and Smith (2001) used a similar strategy and identified 54 scales. Several recent reviews of the available PROMS have been published (Bent et al., 2009; Rodriguez-Merchan 2012; Collins et al., 2011); unfortunately none of these are systematic in their strategy for selecting PROMs. Whilst both Bent et al. (2009) and Collins et al. (2011) provided a robust review of psychometric properties, neither provided a method by which a scale might be selected as preferred. Given the lack of consensus and absence of evidence suggesting superiority of any individual PROM, recommendations from the British Association for Surgery of the Knee (BASK), European Society of Sports Traumatology (ESSKA) and American Orthopaedic society for Sports Medicine (AOSSM) were followed to select the international knee documentation committee subjective knee form (IKDCSKF) as the primary knee function measure (Collins et al., 2011; Irrgang et al., 2001).

The IKDC SKF was designed to unify assessments across the knee injury literature and is therefore not specific to the ACL injured population. Whilst the development process might be criticised for limited patient involvement in item selection and reduction, both Tanner et al. (2007) and Hambly and Griva (2010) have since demonstrated the importance of all items on the IKDC SKF to large samples (n = 153 and n = 141 respectively) of ACLR subjects . Item response theory used during the generation of the tool concluded that the scale was a one dimensional assessment of knee function Irrgang et al. (2001). However this has been contested in a more recent and thorough analysis from Higgins et al. (2007) who identified 14 items relating to function and 4 items relating to activity limitation. The relative size of the factors indicates that the measure is predominantly a measure of symptoms and it can be argued that despite the activity element defined by Higgins et al. (2007), the scale measures symptoms with activity, rather than participation in those activities. The scale is considered reliable with ICC's for test retest reliability >0.9 (Irrgang et al., 2001) and internal consistency >0.8 (Higgins et al., 2007). Minimal detectable change has been reported between 8.8 and 15.6 (Collins et al., 2011) and SEM between 3.2 and 5.6 (Collins et al., 2011). The scale is responsive with MCID of 11.5 points (Irrgang et al., 2006) in a general knee injured population. Specific values for the ACLR population are not available. Due to the joint specific nature of the IKDC SKF, a complementary ACL specific measure was also required. Once again the absence of a gold standard led to the selection of the Lysholm knee scale, since it is well validated and was part of the existing clinical review structure.

The Lysholm scale was introduced by Lysholm and Gillquist in 1982 as an amendment to the modified Larson scale. It is the most frequently cited of the knee rating scales (Lysholm and Tegner, 2007) and has been investigated for measurement properties in ACL reconstructed (Briggs et al., 2009) and meniscal injured (Briggs et al., 2009) subjects. Whilst these studies have been shown to have deficiencies by recent standards (Letchford et al., 2014), they do provide a degree of assurance of adequate measurement properties, that has also been concluded by Collins et al. (2011). It should be noted that the Lysholm was originally introduced as a clinician completed measure, but has become adopted and investigated as a PROM (Collins et al., 2011; Briggs et al., 2009). This adaptation represents a positive step since Roos et al. (2001) have demonstrated significant bias resulting from clinician reported tools, and recommended PROMs. The Lysholm score is generally reported at arbitrarily selected rankings where a score of 95 to 100 is considered excellent, 84 to 94 is good, 65 to 83 is fair, and <65 is poor. Although normally reported as a combined score, the Lysholm scale has also been investigated when reported as subscales. Of interest to this study, the instability subscale has been found to be highly reliable (ICC=0.92) and responsive

(SRM=0.94), with no ceiling effects in a sample of ACL reconstructed individuals (Briggs et al., 2009). This can therefore act as an appropriate measure of functional stability in this sample.

Also of importance to this study both the IKDC SKF (Andersson et al., 2006) and Lysholm (Briggs et al., 2009) have normative data available from large cohorts of healthy Americans. The more comprehensive data set is available for the IKDC SKF; Andersson et al. (2006) used 5246 data points to create age and gender matched normative values with centiles. Briggs et al. (2009a) drew on a much smaller sample of 488 subjects, and as a consequence present just a mean score of 94 in the healthy sample. They make recommendations that a scoring system of excellent (90-100), good (80-90), fair (65-79) and poor (<65) on the basis of representation of 75%, 17%, 8% and 1% of the healthy population respectively.

Knee function in ACLD subjects

There is no doubt that function is reduced in ACLD subjects, and that some recover with rehabilitation whilst others do not (Muadi et al., 2007; Mosknes and Risberg, 2009; Grindem et al., 2012). Muadi et al. (2007) provided a well conducted systematic review of the ACLD literature. From the 8 identified studies using the Lysholm score, they are able to synthesise a mean score of 87% for chronic ACLD (> 60 months), however there is no data available for the early post injury phase (<1 year). Taggesson et al. (2008) have reported a mean Lysholm score of 68 (range 32- 94) at mean 43 days (range 20–96) following injury, Grindem et al. (2012) report IKDC SKF of 72.4 +/- 11 at 74 +/-31 days from injury. Zatterstrom et al. (1998) report Lysholm scores of 79 (range 22-100) after a 6 week rehabilitation intervention beginning following arthroscopic assessment 10 days after injury. The wide SD's and ranges reported in these studies also highlight the variability in knee function that exists between individuals.

The most appropriate comparator for this study is a non-coping ACLD group, who are most appropriately represented by the pre-operative scores reported from studies of ACLR (Table 5). Again there is a large amount of variability in the distribution of these scores within and between groups. These differences are likely to be a reflection of the severity of injury and factors such as time from injury and interventions.

Table 5: IKDC (max = 100) and Lysholm (max = 100) reported at short term (<2 years) following ACLR

Study	n	Time post-op (months)	Scale	Mean (SD or range)	
				Pre	Post
Xergia et al., 2013	22	12	IKDC	na	72 (89)
Lentz et al., 2012	52 (RTS) 42 (not RTS)	12	IKDC	na	94 (6) 78 (16)
Grindem et al., 2012	69	12	IKDC	67 (13)	85 (12)
Logerstedt et al., 2012	93	6 12	IKDC	na	83 (13) 91 (11)
Moksnes et al., 2009	125	12	IKDC	64	87 (2)
Thomeé et al., 2008	38	12	Lysholm	na	87 (11)
Maletis et al., 2007	99	12	Lysholm	64	95
Gobbi et al., 2006	100	12	Lysholm	50	90
Risberg et al., 1999	109	12	Lysholm	na	88 (11)
Ahlden et al., 2012	141 (Male) 103 (Female)	24	Lysholm	73 (24-100) 66 (22-99)	89 (23 –100) 85 (28 – 10)
Spindler et al., 2011	395	24	IKDC	45 (34-56)	75 (66-83)
Stein et al., 2006	23	24	Lysholm	na	92 (61 – 100)

Key: n = number of subjects, RTS = Return to sport, IKDC = International knee documentation committee subjective knee form. Note that Spindler et al. (2011) are median and IQR

Knee function in ACLR subjects

The available literature shows evidence of significant improvements in function following ACLR as measured by the IKDC SKF and Lysholm knee score. It is however not easy to synthesise reports of functional outcome after ACLR. A well conducted systematic review from Reinhardt et al. (2010) demonstrates clearly the differences in methodologies, follow up times and measurement tools, and the poor quality of reporting in many studies. The high quality studies used large cohorts from national registries and showed significant improvements in functional outcomes at one year (Ahlden et al., 2012) following ACLR. A majority of reports using IKDC SKF and Lysholm are of midterm outcomes beyond 2 years (Jerre et al., 2001; Andersson et al., 2001; Ott et al., 2003; Asik et al., 2007; Spindler et al., 2005; Tambe et al., 2006; Asik et al., 2007; Sajovic et al., 2008; Roe et al., 2005; Osti et al., 2010; Hussain et al., 2012) or longer term outcomes beyond 10 years (Mykleburst et al., 2003; Drogset et al., 2006; Salmon et al., 2006; Moller et al., 200; Buchner et al., 2007; Meunier et al., 2007; Kostogiannis et al., 2007; Ferretti et al., 2011).

Papers that were identified reporting IKDC or Lysholm scores at 1 year following ACLR using a pre post analysis are presented in table 5. These studies all demonstrate improvements in function one year after ACLR. However they do not allow us to comment on recovery to the normal levels of knee function that was established earlier as expected by patients. Herrington (2013) has made comments on this difference between improvement and recovery, providing a seemingly useful review of the recent literature reporting IKDC SKF in the ACLR population in comparison to healthy values. The study concluded that normative IKDC values are often not achieved; however this conclusion seems to require more robust support than is presented in the paper. The methods for selecting articles are not systematic; therefore bias in article selection is unknown and of the seven papers cited as demonstrating a lack of recovery 4 have mean values above the healthy standard that was set. There is however more evidence available from the non systematic search carried out for this thesis. There is weak evidence from Jamshidi et al. (2005) who reported that subjects over 6 months from ACLR scored significantly less on the IKDC SKF than a matched healthy cohort. This sample is very small (n = 11 ACLR and N = 10 healthy) and there is missing information in the paper with regards details of follow up and measurement. However, there are more useful contributions. Harreld et al. (2006) present the IKDC SKF scores from a large (N= 206) postal survey of ACLR subjects using clinical significance methods with scores standardized to the age and gender matched normative values published by Anderson et al. (2006). They reported that at > 2 years from surgery, 35.5 % of patients were above the healthy mean, 28% within 1 SD, 19 % within 2 SD and 19% greater than 2 SD from the healthy mean. This is an American sample with high pre-injury activity levels and early surgical reconstruction. Similarly, Logerstedt et al. (2012) reported that 77% of subjects were within age matched IKDC (Andersson et al., 2006) at 1 year after ACLR. Using a different methodology, McAllister et al. (2003) demonstrated similar effects beyond two years from surgery; athletes who had ACLR reported significantly lower Lysholm scores than their uninjured teammates. Interestingly, Grindem et al. (2011) reported similar results 1 year following non surgical management of ACL injury; 76% subjects were within age matched IKDC SKF values. These studies show that normal function is possible at 1 year following ACLR, however there remains a substantial proportion for whom improvement is not the same as recovery, reinforcing the need to consider the clinical significance of change and residual deficits in the context of healthy comparisons.

Recovery of knee function following ACLR

Just three longitudinal studies assessing recovery of knee function following ACLR were identified. Risberg et al. (1999) measured Lysholm in 120 subjects at 3, 6, 12 and 24 months following ACLR surgery and demonstrated significant differences at the first two intervals. However after 6 months from surgery there were no significant differences. Smith et al. (2011) performed a longitudinal follow up of 17 subjects with data collected at 1, 2, 3, 4, 6 and 12 months following ACLR. Whilst the study was focussed on the assessment of passive stability, PROMs data including the Lysholm score were included. Analysis of the PROMs data using repeated measures ANOVA indicated that Lysholm scores improved early after surgery, before reaching a plateau with no further significant change after 4 months. Finally, Alcock et al. (2012) studied the recovery of lower extremity functional scale (LEFS) after ACLR. They demonstrate a non linear recovery with rapid improvements over the first 8 weeks, which slowly tapered off by week 16. These studies all agree that recovery of self reported knee function is initially rapid, with a plateau occurring between 4 and 6 months following surgery. Again, these studies do not allow comment on whether this improvement constitutes full recovery. However, in combination the studies reviewed indicate that there seems to be incomplete recovery over the first 4 to 6 months with limited improvement thereafter. This may have implications for extending rehabilitation periods and maximising the effects of intervention in the early period.

Predictors of knee function at 1 year following ACLR

PROMS derived measures of function have been used as the dependant variable in predictor studies of outcome less than 2 years following ACLR. However as previously mentioned, the lack of consensus has led to multiple tools and difficulties in synthesis of this information. There is evidence of a relationship between functional outcomes and intra-articular injury (Ross et al., 2002; Kowulchuk et al., 2009; Eitzen et al.,2009; Ross et al., 2010); age (Laxdal et al., 2005), BMI (Kowulchuk et al., 2009; Spindler et al., 2011); smoking (Spindler et al., 2011; Kowulchuk et al., 2009); time to surgery (Ross et al., 2002; Laxdal et al., 2005); self-efficacy (Thomeé et al., 2008); fear avoidance (Ross et al., 2010); quadriceps strength (Ross et al., 2002; Eitzen et al., 2009; Logerstedt et al., 2013); pain (Heijne et al., 2009; Eitzen et al., 2009); SLHD (Ross et al., 2002); and ROM (Shelbourne and Grey, 2009). Whilst function scores have been used as the dependant variable in predictor models of success after ACLR, no studies were identified that had assessed function scores as predictors of outcome at 1 year following ACLR.

Pain

ACL injury is often accompanied by acute pain and swelling. Longstanding ACLD and ACLR have both been associated with the development of anterior knee pain (Niki et al., 2012; Culvenor et al., 2013; van der Veld et al., 2008). Visual analogue scales are considered a simple and widely accepted measure of pain intensity (Hawker et al., 2011). A recent review of pain measures indicated that VAS has appropriate measurement properties. There has however been debate in the literature with opposing views over the measurement level of the VAS. Kersten et al. (2012) presented an argument for ordinal level of measurement on the VAS. However a response from Price et al. (2012) cites many studies providing very convincing evidence that the VAS data behaves as an interval / ratio scale, which is the stance taken within the analysis of this study data.

In summary, self reported knee function is most commonly measured using PROMs. Whilst many have been developed there is currently no gold standard or international consensus. The IKDC SKF and Lysholm scales fulfil the requirements of joint and condition specific measures, have been appropriately validated and allow comparison to published age and gender matched healthy normative values. These PROMs have demonstrated variable levels of impairment in ACLD subjects and significant improvement following ACLR. There is a lack of studies appropriately assessing recovery of knee function, however there is indirect evidence that subjects often fail to recover to healthy within the first year. Further investigation of these outcomes in relation to recovery is therefore justified.

Participation

Participation is defined as involvement in life situations (WHO ICF, 2001), however in the ACL injured population the focus has been on physical activity and sport where injuries most often occur (Ahlden et al., 2012). Both a desire and/or inability, due to functional instability, to return to participation in these activities are considered indications for ACLR (Cook et al., 2008) which aims to restore the ability to return to participation in pre-injury activities (Eckstrand, 2011; Lynch et al., 2015). Injured subjects consider return to participation in pre-injury activities an important determinant of success of ACLR (Grindem et al., 2012; Kvist, 2004; Ardern et al., 2011; McCullough et al., 2012; Kocher et al., 2002; Swirtun et al., 2006; Heijne et al., 2008; Thorstensson et al., 2009). There has also been questioning of the appropriateness of recommending a return to high levels of sports participation after ACLR, where there are concerns that this represents a scenario of knee abuse (Ekstrand, 2011; Kvist 2004), where re-injury (Borchers et al., 2009) and earlier onset of degenerative joint disease (Butler et al., 2009) are common. An assessment of return to participation on its own is of limited value as subjects may do so despite significant problems with the knee (Noyes et al., 1991). Whilst some may criticise the use of return to pre-injury participation as a measure due to its multifactorial nature, this is the factor which gives it strength as a holistic outcome for those subjects for whom it is a primary aim (Reider, 2012). There must be a balance in the measures of participation and those of knee function and activity. Despite the importance of participation to injured subjects it remains difficult to advise on the likelihood of attaining a desired level of participation (Reider 2012; Lee et al., 2008), since we are yet to fully understand how successful rehabilitation and surgical intervention are in achieving this goal, or which modifiable factors may influence it. This section will provide a review of the literature reporting participation outcomes.

Measuring participation

The absence of a gold standard measure for participation in the ACLR population leads to a wide variety of methods being employed, introducing inconsistencies in measurement across studies (Warner et al., 2011). This variation in measurement makes synthesis of the literature very difficult to perform. By including only those studies where return to sports participation is presented, or can be calculated, as a percentage of the total number in the cohort, Ardern et al. (2011a) have partially resolved this issue. Whilst the data is suitable for meta-analysis, the issue of what is being measured remains. In order to inform the selection of a PROM for the assessment of participation in the population of this study, a systematic review was performed to identify and evaluate existing methods. This has subsequently been published (Letchford et al., 2012). The systematic search identified 31 different rating scales from 241 outcome studies, most of which had not received appropriate validation for measurement properties. No single measure was considered adequately investigated and additional comparative analysis of the four most commonly applied and appropriately validated tools was recommended. This has also been conducted within this study and published (Letchford et al., 2015). The outcome is presented within the results section.

Participation following ACL reconstruction

Participation outcomes have proved to be highly variable (Ardern et al., 2011a), difficult to interpret and often lower than might be anticipated (Reider et al., 2012). The simplest outcomes to interpret are those which consider the percentage of a cohort returning to sports (RTS) participation. Reports vary from as low as 18% (Sandberg and Balkfors, 1988; Aglietti et al., 1994) to as high as 100% (Nakayama et al., 2000; Muellner et al., 1998; Fabbriciani et al., 2005; Makihara et al., 2006; Marcacci et al., 1999), with many in between 51% (Corry et al., 1999) 52% (Feller and Webster, 2003) 62% (Lee et al., 2008), 79% (Aglietti et al., 2004), 81% (Smith et al., 2004), 88% (O'Neill et al., 1996), 94% (Jennings et al., 2003).

A synthesis of the literature has recently been performed by Ardern et al. (2011a), in the form of a systematic review and meta-analysis. The methodology is conducted and reported in accordance with the PRISMA guidance. Comprehensive strategies are used to search, appraise and extract data from the relevant literature up to April 2010. Meta-analysis of data from the 48 included studies provides an overall rate of return to any sports participation of 82% (95%CI 59-92%). However just 62% (95%CI 51-72%) returned to pre-injury participation levels and only 44% (95%CI 20-69%) to competitive sports. The wide confidence intervals associated with each of these measures clearly demonstrates the variety in RTS rates reported in the literature. This is a theme which continues in the 8 studies reporting RTS rates that have been published since the Ardern et al. (2011a) review, where return to any sport rates vary from 51% Czuppon et al. (2011), 66% (Ardern et al., 2012), 67% (Ardern et al., 2011), 72% (Brophy et al., 2012), 86% (LaBoute et al., 2010); and return to pre-injury sports from 43% (McCoulough et al., 2012), 45% (Ardern et al., 2012a), 61% (Brophy et al., 2012), 63% (Shah et al., 2010), 65.7% (LaBoute et al., 2010) and 68% (Grindem et al., 2012).

This variety is perhaps not surprising when considering a complex construct such as participation, which may be affected by a variety of functional impairments, activity restrictions, environmental and social interactions (WHO ICF, 2001). Understanding these interactions will be important to understanding participation restrictions and developing strategies to reduce them in the future. However, there must also be consideration of methodological issues that may explain these variations and in particular the methods of measuring participation (Reider et al., 2012).

Recovery of participation following ACLR

An understanding of recovery and especially when a return to participation in pre-injury activities will be possible is of importance to patients following ACLR (Heijne et al., 2008). In a narrative review of the rehabilitation literature, Kvist (2004) identified 31 papers which offered recommendations on timing of return to sport. Recommendation ranged between 3 and 12 months, 23 authors recommended 6 months or sooner with just 2 recommending a full 12 months. In the outcomes literature we see similar variety and much longer times than these rehabilitation recommendations suggest. Whilst Shelbourne et al. (2009) reported some subjects returning to sport at a mean 4.6 (+/-1.9) months, these were all high school athletes and when considering older subjects (>25 years) the mean time was 6.1 (+/-2.0) months. In a review of 8 papers on sports specific outcomes, Warner et al. (2011) reported RTS between 3 and 12 months. Ardern et al. (2011) reported a mean of 7.3 (range 2-24) months to return to sport from the meta-analysis. Brophy et al. (2012) reported a mean of 12.2 (+/- 14.3) months. Even in the professional sporting environment, where timing and quality of surgical and rehabilitation interventions are often considered to be optimal, return to play is reported between 6 and 7 months for European football (Walden et al., 200) and a mean 10 months in rugby (Carson and Polman, 2012).
Temporally based rehabilitation programmes are slowly being superseded by a new focus in criterion guided rehabilitation (Kvist, 2004; Hartigan et al., 2010; Adams et al., 2012). Decisions regarding rehabilitation progression and return to activity participation are based upon specific criteria, including objective assessments of functional impairment and activity restrictions. In these programmes the answer to the question of when to return to sport becomes an answer of when you pass the tests, a goal oriented approach that is familiar to

many sports people (Elphinstone, 2008) and has positive influence on rehabilitation adherence and outcomes (Levy et al., 2008). Hartigan et al. (2010) have applied such a rehabilitation guideline and reported on the timings at which the final RTS criteria are passed within a cohort of 40 subjects. The earliest subjects were allowed to take the test was 3 months, at which point 5% passed, by 6 months that had risen to 48% and 12 months 78%. Whilst failures were distributed among all the criteria, the most common reason (75%) for failure of the test at the 12 months was a low quadriceps strength index. Whilst these subjects were passed as ready for RTS there is no way of knowing who was successful in returning to pre-injury participation.

The rehabilitation guidelines therefore create an unrealistic expectation of recovery following ACLR. This is of concern since Heijne et al. (2008) have demonstrated a negative impact of this on the rehabilitation process and eventual RTS. They used semi-structured interviews to study the experiences of 10 competitive athletes during the rehabilitation process. All subjects expected to recover faster than the average (6 months) that had been discussed by the surgeon. None were ready to return to sport at 6 months, which led to feelings of disappointment, and failure, which for some, led to ambivalence, abandonment of rehabilitation and a failure to return to sport.

Factors explaining participation restrictions

The current evidence indicates that ACLR and rehabilitation remains of limited success in returning subjects to their pre-injury levels of sports participation. When considering factors which may be responsible for this Reider (2012) suggested the three categories of impairment functional, psychological and social.

Functional impairment of the knee is reported as the primary cause of participation restriction in 22% (Lee et al., 2008), 33% (McCoulough et al., 2012), 54% (Ardern et al., 2011b), 56% (Ardern et al., 2012a) and 66% (Gobbi and Francisco, 2006) of subjects that elect not to return to sport. However there is also evidence of a poor relationship between PROM measures of knee function and participation restrictions, suggesting that these perceived deficits are not being appropriately measured in the PROMS data. Ardern et al. (2011) reported that successful RTS was no more likely (risk ratio 1.05 95% CI 0.81-1.4) in subjects with good knee function when compared to those with poor knee function according to the categories of the IKDC 2000 form. A similar pattern emerged in the Ardern (2012) study where the symptom scale of the KOOS was poorly correlated to RTS. It therefore seems important to consider the relationships between more specific measures of functional recovery and participation outcomes (McCullough et al., 2012), the use of objective testing has been recommended and required more investigation (Kvist, 2004; Cook et al., 2008).

Two psychological theories have been applied to the ACLR population in the context of explaining participation restrictions; fear of re-injury and self-efficacy.
Fear of re-injury is known to interfere with recovery from musculoskeletal injury and has been associated with the development of functional impairments and participation restrictions in several patient populations (Carson and Polman, 2012; Tripp et al., 2007). Studies have identified fear as a significant factor in determining a subject's decision to return to participation in pre-injury activities following ACLR (Jennings et al., 2003; Kvist, 2004; Tripp et al., 2007: Heijne et al., 2008; Lee et al., 2008, Ardern et al., 2011b; Ross, 2010). Fear of reinjury is reported to be responsible as the primary cause of participation restriction in 17% (Gobbi and Francisco (2006), 18% (Ardern et al., 2011b), 25% (Kvist et al., 2005), 25% (Lee et al., 2008) and 53% (McCullough et al., 2012) subjects that either elect or fail to return to sport. The study of Tripp et al. (2007), used a hierarchical regression analysis that demonstrated that fear of re-injury was a unique predictor of return to pre-injury sport participation (β=-0.4 p=0.01). Ardern et al. (2012b) demonstrated lower levels of fear of reinjury in those who achieve a successful return to pre-injury participation compared to those who adapt or reduce their activities.
Self-efficacy is the belief about one's ability to perform a task or specific behaviour successfully and has been linked to rehabilitation outcomes. Thomeé et al. (2007 and 2008) have extensively studied its impact in the ACLR population and it is a theme that has emerged in several other studies (Gobbi and Francisco, 2006; Heijne et al., 2008; Brand and Nyland, 2009). Those subjects who demonstrate high levels of self-efficacy are more likely to; have ambitious goals; actively participate in rehabilitation strategies; recover from setbacks and perceive knee symptoms as less severe (Brand and Nyland, 2009); all things which could be expected to positively influence rehabilitation outcomes. Thomeé et al. (2007) developed and validated a tool, the knee self-efficacy scale (K-SES) for use in the ACL

injured population. Regression analysis demonstrated that pre-operative assessments using this tool were capable of predicting return to pre-injury intensity and frequency of physical activity (p=0.016), and Lysholm score (P=0.003) at 1 year post-operative. A similar tool for measuring self-efficacy, the psychovitality questionnaire, has been developed by Gobbi and Francisco (2006). Their cohort study of 100 ACLR subjects demonstrated significant relationships between pre-operative psychovitality scores and success in returning to pre-injury sports participation at 1 year following surgery. Unfortunately there is insufficient description of the tools development and measurement properties to be able to make robust recommendations for its use in clinical practice.

Many studies (Heijne et al., 2008; Kvist 2004; Lee et al., 2008; Gobbi and Francisco, 2006; Jennings et al., 2003) reported subjects electing not to return to pre-injury participation due to personal reasons, unrelated to knee function or fear of injury. Social reasons are reported as the primary cause of participation restriction by 17% (Gobbi and Fransisco, 2006), 52% (Lee et al., 2008), and 75% (McCullough et al., 2012) of subjects that elect not to return to sport. Subjects frequently report dedicating time to work, family and other less provocative sporting and physical activities rather than those participated in prior to injury.

Predicting successful return to pre-injury participation

The ability to predict successful RTS after ACLR from a pre-operative assessment would provide valuable information which both clinicians and injured subjects could use to inform the selection of intervention options. Such predictors have been investigated in the study of Hartigan et al. (2012). This robustly conducted study used regression techniques to assess the predictive relationship between age, pre-operative quadriceps strength and external knee flexion moment in gait at the pre-operative assessment and success in achieving return to sport criteria at 6 months post-operatively. They found that all three variables were independent predictors and when used collectively could predict 69% of those that pass and 82% of those that fail. The study further demonstrated that strength gains during a pre-operative rehabilitation programme were highly predictive (63%) of those that passed RTS criteria at 6 months. This has important implications for the implementation and design of preoperative rehabilitation programmes. These methods require the use of expensive and time consuming isokinetic and 3D motion analysis, rarely available in the clinical environment. There remains a need to investigate simple, cheap and efficient alternatives.

In summary, it is clear from the literature that there is variation in the reported success of ACLR and rehabilitation to restore participation in pre-injury activity. It remains to be shown if this variation in outcomes is due to methodological and sampling differences or to genuine variation in the construct with the interventions that were applied. Standardisation of the reporting of RTS using appropriately validated measurement instruments will be important in resolving this debate. Taken as a whole the evidence suggests that success in returning to pre-injury participation is lower than we might either expect or wish, and requires more time to achieve than is frequently suggested. There is clear evidence that social and psychological influences are responsible for participation restrictions in a significant number of individuals. There are also a significant number of individuals who report feeling limited by functional impairment of the reconstructed knee, which is not identified with clinical examination or function questionnaires, but may be identified through objective tests of performance. Further investigation of the relationship between participation restrictions and performance tests is required.

Activity

Activities are most often assessed through objective functional tests which use performance parameters such as speed or distance to define activity restrictions. These tests provide a measure of whether the task is completed but not how it is completed and so does not inform the therapist of why a deficit is present or how to proceed with rehabilitation interventions. Performance tests are also context dependant and performance in the clinic may not translate to performance in alternate situations, such as on the field of play (Shumway-Cook and Woolacott, 2012). For these reasons strategy is considered an important aspect of functional testing (Shumway-Cook and Woolacott, 2012). The assessment of movement strategy is a central component of many assessment and treatment methods (Elphinstone, 2008; Comerford and Mottram, 2001, Shumway-Cook and Woolacott, 2012; Page et al., 2009; Sahrmann, 2002) for musculoskeletal disorders.

Clinical assessment of neuromuscular adaptations and movement strategy has been recommended to guide individualised patient management after ACL injury (Hurd et al., 2008). However, clinically applicable methods remain very limited. Biomechanics offers the opportunity to obtain objective measures of human movement strategies and have identified a variety of adaptations in ACL injured subjects (Augustson et al., 2006; Orishimo et al., 2010; Oberlander et al., 2012, 2013; Gokeler et al., 2013) and could offer a measure of functional recovery to guide rehabilitation interventions (Hurd et al., 2008). However, modern motion analysis methods are often reliant on large scale, expensive and time consuming laboratories. The development of methods which translate the ability to conduct and implement the findings of biomechanical studies of movement strategy into the clinical setting are warranted (Fitzgerald et al., 2001; Gokeler et al., 2010; Augustsson et al., 2006; Engelen-van Melick et al., 2013).

Motion analysis in the clinical setting is mostly reliant on visual observations. Reliability of these observational methods has proven to be variable (Chmielewski et al., 2007; Ekegren et al., 2009; Weir et al., 2010; Whatman et al., 2012). Whilst dichotomous outcomes have been shown to be reliable (Ekegren et al., 2009) with Kappa between 0.75 and 0.80, rating over multiple categories, as is common within clinical practice has proven unreliable (Chmielewski et al., 2007; Weir et al., 2010). Whatman et al. (2012) have confirmed this variability, with interrater agreement ranging from slight to almost perfect, with greater agreement amongst experienced clinicians on dichotomous scales. More recently Crossley et al. (2011) have indicated higher reliability (kappa 0.6 to 0.8) for frontal plane assessments using good, fair and poor descriptors. More systematic approaches have been developed; the landing error scoring system (LESS) (Padua et al., 2009) and test of substitution patterns (TSP) (Trullson et al., 2010; Trullson et al., 2011) are 2 tools developed specifically for the ACL injured population. Both methods have demonstrated good reliability in the limited assessments that they have been subjected to (Trullson et al., 2011; Padua et al., 2009). Whilst these are clinically applicable tools that are designed to influence rehabilitation interventions, they both provide categorised assessment of performance and are therefore likely to be of limited use for progression monitoring. Also the LESS is reliant upon both frontal and sagittal plane video and it seems that more accurate objective methods for motion analysis could be utilised with this type of set up.

2D Digital video has been used in a variety of studies within the knee rehabilitation literature (Button et al., 2005; McLean et al., 2005; Stensrud et al., 2011; Poulson and James, 2011; Munro et al., 2012). Poulsen and James (2011) provided a very useful comparison of reliability of observational and objective measures of knee kinematics, using the same video footage and student therapists to extract both sets of data. The observational measures had lower reliability than the objective measures for both interrater (0.46 – 0.87 and 0.97 – 1.0 respectively) and intrarater (0.38 to 0.94 and 0.88 to 0.98 respectively). The use of digital video for the assessment of kinematics during functional movement testing therefore has the potential to offer a more reliable and accurate assessment of performance and strategy.

The selection of three tasks of hierarchical complexity (walking gait, single leg squat and hop for distance) was previously described and each will now be discussed in relation to the available evidence regarding their measurement, deficits and recovery in ACLD and ACLR subjects.

Gait

Walking has been extensively studied in the healthy, ACLD and ACLR populations. The depth of this investigation is well illustrated by a recent and very well conducted systematic review of gait in ACLR subjects from Gokeler et al. (2013). The report follows PRISMA guidelines, the search strategy is comprehensive and the quality appraisal and data extraction processes are robust. The synthesis of 22 studies that include comparisons both between limbs and with healthy controls leaves no doubt that there are significant adaptations to kinematics and kinetics of walking gait in the ACLR population that persist up to the longest follow up study at 5 years. They concluded that on the basis of current evidence it is uncertain whether normal gait mechanics are ever restored. The study of recovery of gait in the clinical setting is therefore a potentially important source of information for informing rehabilitation practice. For the purposes of this study the review will be restricted to the temporo-spatial characteristics of gait that will be assessed and will be considered in healthy, non-coping ACLD and ACLR subjects**.** A systematic search of electronic databases combining the outcome term ‘gait’ with the population terms ‘ACLD’ and ‘ACLR‘ identified 13 papers that were considered appropriate to the scope of this review.

Temporo-spatial characteristics of gait in healthy subjects

Gait velocity has been demonstrated to be reliably reproducible in healthy subjects (Andriacchi et al., 1977), with a typical mean value of 1.36m/s in adult subjects (Perry and Burnfield, 2010). This is supported by a recent well designed systematic review and meta-analysis (Bohannon and Andrews; 2011) which synthesised data from 41 studies and a total of 23,111 subjects to describe mean gait velocity. The grand mean (cm/sec) was stable between 133.9 and 143.3 for men and 124.1 and 139.0 for women. Gait velocity has a linear relationship with step length and cadence, both of which increase to achieve a greater velocity, whilst stance time and support time are inversely related, both reducing as velocity increases (Andriacchi et al., 1977). Gait velocity is known to alter sagittal knee excursion and moments, with higher velocities related to greater flexion (Perry and Burnfield, 2010; Murray et al., 1984) and knee moments (Andriachhi et al., 1977; Kirtley et al., 1985; Zeni and Higginson, 2009) both at initial contact (IC) and during loading response.

Temporo-spatial characteristics of gait in ACLD subjects

The literature search identified 12 studies and 1 meta-analysis addressing temporo-spatial characteristics (velocity, step length and cadence) of gait in ACLD or ACLR subjects. Nine of the papers included data for ACLD subjects and 8 for ACLR subjects; ACLD and ACLR are compared in 4.

The identified meta-analysis was performed by Shi et al. (2010) to assess the literature comparing gait biomechanics in healthy and ACLR subjects. A systematic search is conducted through a comprehensive selection of appropriate electronic databases; however the selected search terms are limited and may therefore have restricted the papers identified. Studies were included on the basis that they include one or more temporo-spatial, kinematic, or kinetic gait variables. However from the 466 papers that reached abstract review only 6 were included. This has proved to be severely limited. The search strategy used for the current literature review has identified an additional 8 papers, all published within the appropriate time frame and with appropriate outcomes which could have been included in this meta-analysis. There is no evidence of formal critical appraisal for study quality, but data extraction was appropriately managed by 2 independent reviewers. The meta-analysis was well conducted following the appropriate guidelines of the Cochrane collaboration (2003). The results indicate a majority of the included gait variables are restored to healthy values following ACLR, with the exception of peak knee flexion and sagittal plane knee excursion, which remain significantly affected. However, the methodological issues are too significant to accept this as a fair representation of the literature available at the time.

Gait velocity

Eight papers provided an analysis of gait velocity in ACLD subjects. Three papers from the same author presented the same sample data with different aims and therefore different comparators (Button et al., 2005, 2006, 2008). A healthy control mean is used as the comparator in 5 of the studies, 2 of which demonstrated reduced gait velocity in ACLD subjects (Button et al., 2005; Gao et al., 2010) and 3 demonstrated no difference in gait velocity in ACLD subjects (DeVita et al., 1997; Lewek et al., 2002; von Porat et al., 2006). Three of the studies compared ACLD subjects, classified to functional groupings based upon return to activities (Rudolph et al., 1998; Button et al., 2006, 2008).

Both papers that demonstrated a reduction in gait velocity (Button et al., 2005; Gao et al., 2010) contained samples within the early post injury period (<3 months), whilst two of the papers demonstrating no difference in gait velocity contain samples further from injury. The sample of Lewek et al. (2002) was up to 6 months from injury and whilst the mean gait velocity was lower than the healthy comparator this difference was not statistically significant. The sample (n=12) of von Porat et al. (2006) was a mean 14 years from injury with no functional disability, and no significant difference in velocity when compared to an age matched healthy comparator group. Both studies are relatively low power (n=10 and n=12 respectively) to detect what is likely to represent a clinically significant difference (7% and 5% deficit respectively). These papers suggest a pattern of reduced velocity in the early post injury phase, which improves with time. The only paper suggesting otherwise is that of DeVita et al. (1997) where a sample (n=9) just 2 weeks following injury had gait velocities similar to a healthy comparator group. Several factors may help to explain this different result; firstly the methodology constrained the gait velocity of the healthy group to 1.5m/s, whilst the injured subjects walked at a self-selected speed. The healthy group also contained a greater proportion of female subjects, who are known to walk more slowly than males (Bohannon and Andrews, 2011).

The final three papers compared ACLD subjects divided into coper and non-coper subgroups on the basis of functional limitations and participation restrictions (Rudolph et al., 1998; Button et al., 2006, 2008). Button et al. (2006, 2008) identified that copers (n= 42) recovered more rapidly and were distinguishable from non-copers at 4 months post injury on the basis of gait velocity. Assessing subjects over 2 years following injury Rudolph et al. (1998) identified a trend towards reduced gait velocity in a non-copers compared to copers. The mean difference of 13% seems clinically significant and the lack of statistical significance may be due to small sample size (n=16).

Step length and cadence

The studies of Button et al. (2005) and Gao et al. (2010) demonstrated a reduced step length in acute ACLD occurring in association with reduced velocity, confirming the presence of the relationship that is seen in healthy subjects (Perry and Burnfield, 2010). In a similar pattern to the recovery of velocity, Button et al. (2005, 2006) demonstrated recovery of step length over time, occurring more rapidly in copers than non-copers. Although, at longer term follow up of a group of non-copers, it was contralateral step length that was significantly reduced rather than that of the injured limb (Button et al., 2008). Knoll et al. (2004) also demonstrated reduced step length in their ACLD sample. Whilst the sample is split into acute and chronic groups on the basis of time from injury (mean 12 days, and 28 months, respectively), analysis is based upon the sample as a whole without assessment of differences between the sub groups. This study was performed on a treadmill with a constrained gait velocity, which is likely to constrain stride length. In contrast, Von Porat et al. (2006) and DeVita et al. (1997) demonstrated no difference in step length; this is most likely due to the same reasons that gait velocity was not different. Just 2 studies assessed cadence. Button et al. (2005) identify a reduced cadence in association with reduced stride length and velocity in acute ACLD, whilst DeVita et al. (1997) again identified no difference from healthy values in their ACLD sample.

Recovery of temporo-spatial characteristics

Just one longitudinal study of gait recovery following ACL injury has been identified. Button et al. (2005) conducted repeated measures of temporo-spatial gait characteristics using a digital video system. There were reductions in cadence, step length, step symmetry and velocity which recovered within 1 SD of the control mean over the 5 month period following injury. Moreover, the time and extent of recovery was capable of predicting longer term (12-36 months) coping status (Button et al., 2006, 2008). Copers recovered all variables above the control mean within 40 days of injury, while non-copers recovered later and only to the lower limits of the control mean (-1SD). They suggested that serial gait analysis may be a more dynamic method for sub classifying subjects than other methods.

The literature contains evidence to indicate that ACLD subjects reduce step length, cadence and gait velocity in the early post injury phase. A process of recovery towards healthy values occurs which is more rapid and more complete in coper than non-coper subjects. Whether a significant abnormality in temporo-spatial gait characteristics remains prior to ACLR in non-coping subjects is as yet unknown.

Temporo-spatial characteristics of gait in ACLR subjects

Gait velocity

Five papers provided an analysis of gait velocity in ACLR subjects, all providing comparison to a healthy control mean (Decker et al., 2004; DeVita et al., 1997; Gao et al., 2010; Lewek et al., 2002 and Bush Joseph et al., 2001). Three papers provided evidence of reduced gait velocity in the early post-operative period (DeVita et al., 1997; Decker et al., 2004; and Gao et al., 2010) and there are no reports to challenge this. A pattern of recovery is again described however the time at which this occurs is varied. DeVita et al. (1997) identified the earliest recovery, their sample reaching healthy control values by 5 weeks post-operatively, although this is a very small sample (n=10). Recovery by 12 weeks post-operatively is reported by 2 studies (Lewek et al., 2002; Decker et al., 2004) and between 3 and 12 months in 1 study (Gao et al., 2010), whilst 1 longer term follow up indicates a normal gait velocity by a mean 22 months post-operatively (Bush-Joseph et al., 2001).

Step length and cadence

Five papers assessed step length and/or cadence following ACLR. Similarly to the situation following injury, reduced step length is reported in the immediate post-operatively period by all studies (DeVita et al., 1997; Decker et al., 2004; Knoll et al., 2004; Gao et al., 2010; Minning et al., 2009) but again the recovery is less well defined. Four papers compared to healthy control means. DeVita et al. (1997) reported an initial reduction of step length and cadence by a mean 13%, which normalised by 5 weeks post-operatively. Both Decker et al. (2004) and Knoll et al. (2004) noted a reduced stride length at 6 weeks post-operatively, which recovered to within normal limits by 12 weeks and 4 months post-operatively respectively. Gao et al. (2010) demonstrated a reduced step length in ACLD subjects prior to surgery that improved following ACLR but did not reach normal values during the 3-12 month study period. Minning et al. (2009) assessed step length in comparison to the contralateral limb and noted a significant asymmetry in the early post-operatively period, with steady recovery until full symmetry was achieved by 12 weeks post-operatively.

Recovery of temporo-spatial characteristics

Just two longitudinal observational studies of temporo-spatial characteristics following ACLR were identified. Knoll et al. (2004) used the Zebris 3D ultrasound system to analyse kinematics and temporo-spatial characteristics of 25 subjects prior to and 6 weeks, 4 months, 8 months and 12 months following bone patella tendon bone (BPTB) ACLR. As previously mentioned there were asymmetries in step length at 6 weeks post-operatively that returned to healthy values at 4 months. Whilst this suggests a pattern of recovery, the disadvantages of symmetry measures and the low number of follow-ups in the early post-operative period limit what we can learn from this. Minning et al. (2009) assessed subjects walking at their preferred velocity on a gait analysis treadmill which calculated step length, stance time and gait velocity, all of which were reduced following surgery and recovered within 3 months. It should be noted that recovery was defined by limb symmetry, the disadvantages of which were previously discussed. Recovery occurred in a similar pattern to that of the ACLD group of Button et al. (2006); step length was the earliest to recover whilst gait velocity and stance time took longer. Interestingly, gait velocity was correlated to functional outcome (KOS ADLS), with regression analysis identifying it as capable of predicting 49% of the variance in this outcome, suggesting that it has the potential to be a predictor of functional recovery.

The literature demonstrates that in a similar pattern to ACLD subjects, ACLR subjects also reduce stride length, cadence and gait velocity in the immediate post-operative period, which follows a pattern of recovery towards healthy values. However the timing and extent of this recovery and its influence on functional outcomes is yet to be appropriately defined. Further analysis of the recovery process, linked to final outcomes and timing of interventions is required if this information is be useful for informing clinical decision making.

Single Leg Squat

Squatting is one of the most popular strength training exercises for the lower limb muscles that is commonly used during rehabilitation of the ACL injured population (Button et al., 2014). Double leg squatting is considered to be more challenging to functional knee stability than gait but less challenging and therefore less provocative than SLHD (Button et al., 2014). Similarly to gait, ACL injured subjects have been shown to alter movement strategy when performing bilateral squats, reducing both sagittal plane ROM and external flexion moments on the injured knee (Button et al., 2014) and reducing power at the knee whilst increasing at the hip (Salem et al., 2003). They have been shown to avoid using the injured limb and increase loading on the contralateral limb by as much as 48% in the early post ACLR phases and even at 12 to 15 months following ACLR loading is more asymmetrical than healthy subjects (Neitzel et al., 2002). These adaptations are important to understand during rehabilitation and have been suggested as one reason that recovery of strength may be incomplete in this population (Neitzel et al., 2002; Salem et al., 2003). Moving the exercise onto a single limb is one way of limiting these adaptations and increasing training load (Minning et al., 2009).
Single leg squat (SLS) is a weight bearing closed chain exercise that combines axial loads (Markolf et al., 1978; Li et al., 1999) with multiple muscle activations and co-contractions (Zeller et al., 2003; Kvist et al., 2005) that increase joint stability, in a manner that simulates many functional tasks. These attributes have made it a commonly utilised exercise for both

strength and neuromuscular (Beutler et al., 2002; Kvist et al., 2005) training. Over time the SLS has been modified for use as a functional test in the clinical environment (Sahrmann, 2002; Mottram and Comerford, 2008; Trullson et al., 2010; Weir et al., 2010; Weeks et al., 2010; Whatman et al., 2012), where subjective ratings of movement quality are applied. Visual estimations or instrumented measures of dynamic valgus (Powers, 2010; Trullson et al., 2010; Crossley et al., 2011), peak knee flexion (Whatman et al., 2011; Yamazaki et al., 2010; Beutler et al., 2002; Kvist et al., 2005) and lateral trunk motion (Weir et al., 2010) have all been used to qualify performance.

SLS has not been sufficiently investigated to understand which parameters are the most important to functional recovery in ACL injured subjects. Weeks et al. (2012) have identified the factors that are important to clinicians when rating motion quality in the SLS. By investigating 3D kinematics as predictors of clinician ratings of motion quality they demonstrated that peak knee flexion was the kinematic parameter that most accurately predicted the assigned level of quality. It therefore seems that clinicians consider Squat depth an important element of SLS performance. Several authors have suggested that peak knee flexion may be useful in determining functional recovery of ACL injured subjects (Beutler et al., 2002; Yamazaki et al., 2010; Button et al., 2014) and this method has therefore been adopted in this study.

Knee loading during single leg squat

Escamilla et al. (2009) used 3D motion laboratory data and biomechanical modelling to estimate ACL loading during SLS in healthy subjects. In this sample, loading of the ACL peaked between 0 and 40 degrees of flexion at 59N, whilst peak strain reached just 2.8% +/- 0.62 (Heijne et al., 2004). Tagesson et al. (2010) used electrogoniometry to demonstrate that there was no excessive anterior tibial translation during SLS at 5 weeks following ACLR. For these reasons, it is suggested as an interim functional measure, which can be safely used in the early post injury and post-operative period (Escamilla et al., 2009; Tagesson et al., 2010; Yamazaki et al., 2010).

Operational definition of single leg squat

A recent review by Bailey et al. (2011) demonstrated a lack of a standardised operational definition and evaluation scheme for the SLS exercise in papers reviewed, although the search strategy did not seem to be particularly systematic, they did identify 12 authors apparently using different methods. Squat depth has been constrained to different flexion angles (Willson et al., 2006; Claiborne et al., 2006; Whatman et al., 2011; Willy and Davis, 2011) to a point where stability can be maintained (Yamazaki et al., 2010, 2013) or unconstrained (Beutler et al., 2002; Zeller et al., 2003; Crossley et al., 2011; Button et al., 2014). There are advantages to constraining knee flexion when addressing frontal plane mechanics (Willson et al., 2006) however when considering self-selected strategy as a marker of recovery these restrictions need to be lifted. Likewise arm motion has been constrained on the hips (Weir et al., 2010), across the chest (Zeller et al., 2003; Crossley et al., 2011) or held out at 90 degrees in front of the body (Livengood et al., 2004) or with finger tips on a supporting pillar (Beutler et al., 2002), which will affect the selected strategy and impact on balance reactions. Moreover, authors used different numbers of repetitions, some resting between each (Beutler et al., 2002) whilst others completed 2 (Yamazaki et al., 2010) or 5 (Zeller et al., 2003; Crossley et al., 2011) consecutively. In order to understand self-selected strategy as a marker for rehabilitation, unconstrained performance of squatting with the instructions “bend the knee as far as you can” seems appropriate.

Measurement properties

Several papers were identified addressing reliability of SLS testing (Whatman et al., 2012; Weir et al., 2010). However these related to the methods by which the data is extracted using various observational outcomes or kinematic parameters. No studies were identified assessing reliability of performance on repeated testing or of using DV to select peak knee flexion angles. The assessment of knee flexion angles from DV using SiliconCoach has demonstrated high test retest reliability (ICC >0.89), although this investigation is limited in numbers (Cronin et al., 2006).

Peak knee flexion during single leg squat in healthy subjects

Four papers were identified reporting healthy values for peak knee flexion during SLS (See Table 6). Although not specifically addressed in any of these papers there does appear to be large variation in performance, the range for normal reported in Weeks et al. (2012) was 57 to 110 degrees of peak flexion. Beutler et al. (2002), Dwyer et al. (2010) and Weeks et al. (2012) all found significantly less peak knee flexion in female subjects than males, however

Zeller et al. (2003) did not. Sample sizes are generally small and only Dwyer et al. (2010) provided power calculation to support adequacy for statistical testing.

Table 6: Peak knee flexion during single leg squat in healthy subjects

Study	n	Peak knee flexion (Degrees)		Sig.
		Male	Female	
Beutler et al., 2002	18	120 +/- 21	96 +/- 19	<0.05
Zeller et al., 2003	18	90 +/- 6	95 +/- 6	0.292
Dwyer et al., 2010	44	67 +/-10	60 +/-13	<0.05
Weeks et al., 2012	22	86 +/-13	72 +/-7	0.001

Key: n = number of subjects. **Note:** Weeks et al. (2012) report an overall PKF of 80 +/- 12 for the group range 57 – 110.

Peak knee flexion during single leg squat in ACLD / ACLR subjects

Four studies addressing biomechanics of SLS in ACLD / ACLR populations were identified (Table 7). Although not the primary focus of the study, Kvist et al. (2005) demonstrated the maximum knee flexion on the injured knee was significantly less than on the uninjured knee (mean difference = 13+/-12 degrees). Of note, anterior tibial translation peaked at 25 degrees and reduced as the knee moved into greater flexion, indicating that this is indeed a safe exercise for graft loading after ACLR. Two papers have been published by a group in Japan (Yamazaki et al., 2010, 2013); both used the Fastrack electromagnetic device to measure kinematics during single leg squatting for maximal depth. The 2010 paper has a larger and mixed gender sample (32 male, 31 female) with acute isolated ACL injury awaiting surgical reconstruction, and 26 healthy controls (14 male, 12 female). The latter paper investigated only female subjects after double bundle ACLR. Both papers identify significant differences both between limbs and between groups. In both studies, knee flexion is significantly reduced on the injured side when compared to the non-injured limb. Whilst this is also the case in the healthy comparison for the male subjects, the female healthy subjects did not squat as deeply. It seems that this is due to a particular performance in the healthy group as the mean knee flexion was only 66 degrees, which seems quite conservative in comparison to healthy values reported by (Beutler et al., 2002) and the values of the non-injured limbs of the subjects in both these and Kvist et al. (2005). Most recently, SLS was investigated alongside other functional tests including SLHD and double leg squat in healthy, ACLD and ACLR subjects (Button et al., 2014). Both ACLD and ACLR subjects were found to squat with less knee flexion, although the deficits were greater in the ACLD group. This is reported in a conference abstract which limits further appraisal.

Table 7: Sagittal plane knee kinematics reported in the literature

Study	Population	n	Time months	Peak knee flexion (Degrees)	
				Injured	Non-injured
Kvist et al., 2005	ACLD	12	27 (17-35)	127 +/- 14	140 +/- 13
Yamazaki et al., 2010	ACLD Male	32	3.5 +/- 1.8	65 +/-19	74 +/-14
	ACLD Female	31		69 +/-13	74 +/-13
Yamazaki et al., 2013	ACLR Female	28	19 (8-28)	71 +/-16	73 +/-17
Button et al., 2014	ACLD	21	unknown	63 +/- 9	unknown
	ACLR	24	unknown	67 +/-14	unknown

Key: ACLD = Anterior cruciate ligament deficient subjects, ACLR = Anterior cruciate ligament reconstructed subjects, n = number of subjects.

The literature indicates that SLS has been adopted as a functional test within the clinical environment where peak knee flexion has been shown to be the most significant factor affecting therapist's perceived quality of the motion. Given the limb stiffening strategy that has been discussed in relation to gait and the reduced ROM described in double and single leg squatting, the assessment of peak knee flexion single during leg squat as a measure of willingness and ability to bend the knee in loaded positions is justified.

Single leg hop for distance

SLHD was first described by Daniel et al. (1982) as a test to quantify functional stability of the knee, that has since formed the basis from which a battery of hop tests have developed to include multiple hops in multiple planes of movement, some of which are repeated to replicate fatigued conditions (Itoh et al., 1998; Gustavson et al., 2006; Hopper et al., 2008;

Thomeé et al., 2012). These hop tests have been suggested for monitoring progress during rehabilitation programmes (Manal et al., 1996; Williams et al., 2001; Hopper et al., 2008) and guiding decisions on return to activity (Kvist et al., 2004; Hopper et al., 2008; Thomeé et al., 2011). SLHD is considered a challenging functional task that places large demand on the knee both to generate joint power in take-off (Rudolph et al., 2000) and to absorb ground reaction forces during landing (Augustsson et al., 2006; Button et al., 2013). Traditionally hop distance is used as a measure of performance; however more recent attention has been focussed on the strategy used during landing (Augustsson et al., 2006; Gokeler et al., 2010; Oberlander et al., 2012, 2013; Roos et al., 2014).

Operational definition

There is agreement that the hop distance should be maximal (Gustavson et al., 2006) and that stability should be maintained on landing, with no onward hop or foot motion (Brosky et al., 1999; Ageberg and Friden 2008; Gustavson et al., 2006; Xergia et al., 2013). Whilst up to 15 trials have been proposed to be necessary to avoid measurement error (Perry et al., 2005) this is impractical in the clinical setting and the mean of three trials are commonly applied (Xergia et al., 2013) in an attempt to get closer to this true value. Some authors constrain the arms, suggesting that this better represents lower limb function (Petschnig et al., 1998; Paterno and Greenberger., 1996; Gustavson et al., 2006), whilst others encourage arm use as a normal part of the movement pattern (Brosky et al., 1999; Ageberg and Friden, 2008) improving relevance to functional situations. Studies utilising arm swing have reported significantly longer maximal SLHD than those that constrained the motion (Ageberg et al., 2001; van der hast 2007; Ashby and Heegaard, 2002). Most authors measure from toe to toe or heel to heel, however some measure from toe to heel (Gustavson et al., 2006; Xergia et al., 2013) which results in dependency on foot and shoe size.

Measurement properties of SLHD

Studies assessing the reliability of SLHD in both healthy (Hu et al., 1992; Booher et al., 1993; Paterno and Greenberger 1996; Bolga and Keskula, 1997; Gustavson et al., 2006; Ageberg et al., 1998; Augustsson et al., 2006) and ACL injured populations (Paterno and Greenberger 1996; Brosky et al., 1999; Ross et al., 2002; Reid et al., 2007) are presented in Table 8. Whilst the studies are generally well performed with appropriate control of important variables and appropriate timescales for retest, most have small sample sizes and are underpowered by modern standards (deVet et al., 2012). However, the ICC values are consistently high across the studies, providing sufficient evidence of reliability of the test. Standard error of measurement (SEM) has only been reported in three studies. Bolga and Keskula (1997) and Ross et al. (2002) reported SEM of 4.56 cm in healthy and 2.41cm in ACLR respectively; whilst Reid et al. (2007) reported SEM for LSI in ACLR subjects at 3.49%. Reid et al. (2007) is the only study to have reported minimal detectable change (MDC) of SLHD in the ACLR population (8.09% LSI).

SLHD in healthy subjects

Hop distance in healthy, ACLD and ACLR subjects from the reviewed studies is displayed in table 9. There is considerable variability in the mean scores that is explained by group differences. There is a consistent effect of gender and age, such that males hop farther than females (Itoh et al., 1998; Ageberg, 2001; Gustavsson et al., 2006; Thomeé et al., 2013) and increasing age is associated with reducing hop distance (Ageberg; 2001). Whilst Ageberg et al. (2001) reported no effect of height, weight and activity level, English et al. (2006) demonstrated that weight is related to hop distance. Gaunt and Curd (2001) found that weight was associated with hop distance but not LSI. Demographic characteristics of the comparator group are therefore important when looking at hop distance and less so when using LSI, perhaps one reason why LSI has become so popular.

Table 8: Studies assessing test retest reliability of SLHD

Study	Healthy		ACLR	
	n	ICC	n	ICC
Hu et al., 1992	30	0.79 - 0.96		
Bolga and Keskula et al., 1997	20	0.96		
Booher et al., 1993	18	0.77 – 0.99		
Paterno and Greenberger, 1996	20	0.92 - 0.96	13	0.89
Brosky et al., 1999	15		15	0.8-0.97
Gustavson et al., 2006	15	0.90 - 0.98		
Ageberg et al., 1998	75	0.96		
Ross et al., 2002	50		10	0.94
Augustsson et al., 2006	11	0.98		
Reid et al., 2007	42		35	0.92

Key: n = number of subjects; ICC = Intraclass Correlation Coefficient, ACLR = Anterior cruciate ligament reconstructed subjects.

SLHD in ACLD subjects

From the literature reporting LSI, it is clear that ACLD subjects have asymmetrical hop performance (Logerstedt et al., 2012, 2013; Grindem et al., 2012) and that hop symmetry improves following rehabilitation in ACLD subjects (Button et al., 2005; Risberg et al., 2009; Grindem et al., 2012). There are however few studies reporting hop distance in comparison to a healthy group and those that did demonstrated that recovery of SLHD is variable (Grindem et al., 2012; Button et al., 2006). Importantly SLHD has been shown to predict future functional instability in ACLD subjects with functional copers recovering earlier than non-copers (Button et al., 2006).

SLHD in ACLR subjects

Again the LSI literature confirmed that symmetry is improved in ACLR subjects (Andrade et al., 2002; Reid et al., 2007; Reinke et al., 2011; Logerstedt et al., 2012; Thomeé et al., 2012) when compared to ACLD. It is also apparent that whilst the gains in symmetry may be significant and meet the a priori symmetry standards of 90% at group level (Ageberg et al., 2008; Logerstedt et al., 2013), they often do not (Andrade et al., 2002; Mattacola et al., 2002; Gokeler et al., 2010). At the individual level there are significant numbers of subjects who continued to have large asymmetries in hop performance (Thomeé et al., 2012). Two comprehensive longitudinal studies of hop performance in ACLR subjects have been published by Thomeé et al. (2012) and Logerstedt et al. (2013). By following subjects from baseline after injury through prehabilitation and surgery up to 12 months (Logerstedt et al., 2013) and 24 months (Thomeé et al., 2012) they have been able to show the pattern of recovery of hop LSI. Both studies demonstrate significant improvements in symmetry with large effect size (0.9 – 1.1) reported by Logerstedt et al. (2013). Both studies demonstrated that pre-operative performance (after prehabilitation) is similar to that at 6 months post-operatively, whereas by 12 and 24 months it has improved further. Recovery of performance beyond pre-operative levels is therefore not expected before 6 months post-operatively. In contrast to other studies that have managed missing data poorly (Nyberg et al., 2006), Logerstedt et al. (2013) used full information maximum likelihood to account for the small amount of missing data. There is no mention of missing data in the Thomeé et al. (2012) paper.

Due to this predominance for the use of LSI in the literature there are very few studies reporting raw hop distance for ACLD and ACLR subjects. Those that were identified are presented in Table 9. This data seems to support the opinion of Thomeé et al. (2012) that there is large variability in performance of SLHD in the ACL injured population. It also supports the notion that ACLR subjects do not recover to the performance of matched healthy individuals that has been demonstrated by both Roos et al. (2014) and Matacolla et al. (2002). Whilst there is data that supports incomplete recovery following ACLR the extent of the deficit from healthy remains poorly defined. There is also limited understanding of SLHD in the earlier phases of rehabilitation between 3 and 6 months, when its use as a clinical milestone has been suggested (Adams et al., 2012).

Recovery of SLHD following ACLR

Improvement in SLHD performance beyond pre surgical values has been shown from as early as 4 months (Andrade et al., 2002). However these differences have failed to reach statistical significance until 6 (Keays et al., 2003); 8 (Andrade et al., 2002); and even 12 months (Nyberg et al., 2006) following surgery. Reid et al. (2007) demonstrated significant differences in SLHD performance over the period between 16 and 22 weeks following ACLR, suggesting that gradual changes through rehabilitation occur. These improvements have been shown to continue for up to 3 years (Ageberg et al., 2008; Nyberg et al., 2006). Whilst the data of Nyberg et al. (2006) is very attractive as a model for recovery, there is a significant missing data issue which is not well explained or discussed and is managed with casewise deletion prior to repeated measures ANOVA which runs considerable risk of biased parameter estimates (Graham et al., 2009).

Hop tests as predictors of success

Hop tests have been shown to be useful for discriminative purposes (Rudolph et al., 2000; Fitzgerald et al., 2001). However understanding of their predictive use is limited. Four papers have been identified that address hop tests as predictors of short-term outcome. The earliest paper is from Reinke et al. (2011) who studied a series of subjects greater than 2 years following ACLR. They found a moderate (r=0.3-0.5) correlation between SLHD and IKDC SKF (function) and that SLHD predicted 32% of the variance in the IKDC SKF outcome. Correlations in the participation domain were however weak (r<0.3) for KOOS sport and recreation and non-significant for the Marx activity rating scale. SLHD LSI therefore demonstrated capability to predict functional outcome but not participation. Interestingly they included a simple quality variable, counting the number of SLHD tests that were not allowed due to faults on landing, this was a significant contributor to the predictor model for both of the participation outcomes. Reinke et al. (2011) suggested that the subjects are pushing themselves to perform beyond their physical capabilities, which are leading to less stability on landing and hence increased faults. Conversely it might be suggested that fear of reinjury is limiting those with low number of faults to act within their capabilities and limiting the performance that is measured. This suggests that landing strategy may also be an important measure that might be used alongside performance parameters to identify those that are exceeding their capabilities through altered movement strategies.

The Oslo-Delaware collaboration has produced 2 articles looking at predictive capabilities of hop tests in ACLD and ACLR populations. Grindem et al. (2011) found that SLHD performed after initial rehabilitation (mean 74 +/-31 days from injury) was a predictor of IKDC SKF at 1 year following rehabilitation management of ACL injury. Following the model proposed by Fitzgerald (2001), age and gender matched normative values were used to define recovery and the optimal cut off on receiver operating characteristic (ROC) analysis was 88% LSI. Sensitivity was 71% and specificity 72%, positive likelihood ratio of 2.52 and negative likelihood ratio of 0.40. This suggests that SLHD can be used to predict function after rehabilitation management. There was an issue with missing data for 10 (11%) subjects that is not well explained and managed by list wise deletion. Whilst this is unlikely to have a dramatic effect on parameter estimates, other methods would be preferable (Graham, 2009). In the ACLR arm of the study, Logerstedt et al. (2012) demonstrated that whilst pre-operative hop LSI was not a predictor of IKDC SKF at 1 year following ACLR, the 6 months post-operatively tests were. The ROC analysis gave an optimal cut off at 89% LSI, with sensitivity of 0.53, specificity of 0.72, PLR = 1.9 and NLR = 0.65. The full barrage of hop tests were include in the study and it is interesting that the test that is suggested to be the simplest (Gustavson et al., 2006) from the perspective of knee stability (6m timed hop) is also the one with the greatest predictive capabilities. Again there is inadequate description of missing data mechanisms, however in this case with up to 33% missing data and what

Table 9: Studies reporting single leg hop distance in Healthy, ACLD and ACLR subjects

	Healthy		ACLD			ACLR		
Study	Gender	Hop distance (cm)	Time from surgery (months)	Distance (cm)		Time (months)	Distance (cm)	
				Injured	Non Injured		Injured	Non Injured
Paterno and Greenberger 1996	Both	150 +/- 23				8 +/-3	147 +/- 33	168 +/- 25
Gustavson et al., 2006	F M Both	137 +/- 13 160 +/-11 151 +/- 16	11	115 +/- 39	135 +/- 29	6	128 +/- 28	148 +/- 23
Reid et al., 2007	Both					5	141 +/- 28	160 +/- 26
Itoh et al., 1998	M F	193 +/- 19 149 +/- 14						
Ageberg et al., 2001	Both	203 +/- 21						
Ross et al., 2002	Both					>12	186 +/- 27	
Matacolla et al., 2002	Both	188 +/- 29				18 +/- 10	174 +/- 28	193 +/- 22
Keays et al., 2003			31 +/- 43	123 +/- 38	150 +/- 27	6	136 +/- 29	155 +/- 23
O'Donnell et al., 2006	Both	175 +/- 5	5 to 60	158 +/- 12	172+/- 18			
Van der Harst et al., 2007	Both	143 +/- 7						
Ageberg et al., 2008			24 - 60	132 +/- 5	134 +/- 4	24 - 60	132 +/- 4	133 +/- 3
Gokeler et al., 2010	Both	143 +/- 6.8				6	94 +/- 19	111 +/- 8
Baltaci et al., 2012	M	177 +/- 12				18-24	133 +/- 25	151 +/- 25

Key: M = Male, F = Female

appears to be the use of case wise deletion; this is likely to represent a greater concern for biased parameter estimates (Graham, 2009). Heijne et al. (2009) studied 68 subjects over a 1 year period following ACLR, losing just 4 to follow up. They investigated a large number of pre-operative predictors for effect on KOOS Sport / Recreation subscale score, Tegner activity rating scale and SLHD LSI measured at 12 months post-operatively. Pre-operative SLHD did not correlate to any of the dependant variables and did not make the predictor models. All four of these predictor studies used LSI and as previously discussed this may underestimate the functional deficit in some subjects and therefore be limiting the correlation and predictive capabilities of the tests. Considering hop tests as predictors on the basis of raw performance scores might improve their predictive capabilities and clinical utility.

In summary, the literature suggests that SLHD is a useful predictor for function outcomes during rehabilitation of ACLD and ACLR subjects; however the ACLR surgery seems to be a 'game changer' and preoperative SLHD is not predictive of post-operatively functional outcomes. It is clear that further investigation is warranted (Grindem et al., 2012).

Single leg hop landing strategy

Whilst there is no doubting the clinical utility of SLHD as a performance measure, there is a strong case that alternative measures may be required to fully define recovery. In their early paper, Tegner et al. (1986) indicated that recovery of performance does not assure functional recovery, as compensatory strategies may exist. It is now widely accepted that strategy is an important aspect of functional testing (Fitzgerald et al., 2001, Orishimo et al., 2010; Augustsson et al., 2006) that can be investigated using biomechanics. Sekiya et al. (1998) suggested that strategies at the knee and other joints including the trunk and upper limbs are worthy of investigation. In their clinical commentary, Fitzgerald (2001) recommended a comprehensive approach to the assessment of neuromuscular control in SLHD landing so that compensatory strategies critical to function could be explored. They highlighted that the research at the time had utilised a variety of tests and methodologies that were difficult to assimilate and draw conclusions from. The literature has however become much more focussed since this time and there are now studies focussed on neuromuscular strategies during SLHD. Currently, these studies have focussed on sagittal plane mechanics as this is where most of the power is generated and absorbed (Xergia et al., 2013; Roos et al., 2014).

The findings of the identified studies are summarised in Table 10. The common finding is related to what has been described as a stiff landing strategy (Gokeler et al., 2010; Laughlin et al., 2011) which is primarily characterised by reduced excursion at the knee (Risberg et al., 2009; Gokeler et al., 2010; Orishimo et al., 2010; Xergia et al., 2013; Laughlin et al., 2011; Button et al., 2014).This is accompanied by reduced external knee flexor moment and what are considered compensatory increases in moments at the hip and ankle (Risberg et al., 2009; Gokeler et al., 2010). This strategy has been identified in ACLD subjects (Button et al., 2014; Risberg et al., 2009) and shown to remain after both rehabilitation (Risberg et al., 2009) and ACLR (Button et al., 2014; Oberlander et al., 2013); in some cases despite achieving acceptable hop performance (Orishimo et al., 2010). The limitation in knee excursion with reduced knee extensor moment is also found in studies of landing strategy during other tasks (Phillips and van Deursen, 2008; Paterno et al., 2010; Pollard et al., 2010; Deneweth et al., 2010). There is concern as this is also a strategy that has been shown to increase ACL loading (Laughlin et al., 2011); has been proposed to increase ACL injury risk (Pollard 2010); and may be implicated in the early development of OA (Deneweth et al., 2010). It is therefore considered potentially undesirable for long-term knee health.

These studies are not without limitations. Some are limited by small sample sizes (Gokeler et al., 2010; Orishimo et al., 2010), which is common in the biomechanics literature where expensive laboratories are required for data collection. There are different approaches to data collection and processing, differences in constraint of the arm motion (Gokeler et al., 2010; Oberlander et al., 2012; Oberlander et al., 2013; Xergia et al., 2013) and the distance of the hop (Oberlander et al., 2012; Oberlander et al., 2013) which may affect the strategy selected. A majority of these studies use the contralateral (non-injured) limb as the comparator which given the previous discussion on the use of limb symmetry may provide conservative estimates of any difference from healthy values. However, regardless of these variations the conclusions are similar and it is therefore likely that this represent a good estimate of altered landing strategy in the population.

Table 10: Summary of studies reporting kinematics and kinetics of SLHD landing strategy.

Paper	Sample	n	comparator	Time from Surgery (months)	Kinematics (joint excursion)				Kinetics (extension moment)		
					Trunk lean	Hip	Knee	Ankle	Hip	Knee	Ankle
Risberg et al., 2009	ACLD	32	Contralateral	<6			↓		↑		↑
	ACLD	32	After rehab			↑					
Gokeler et al., 2010	ACLR	5	Contralateral	6		↓	↓		↑	↓	↑
Orishimo et al., 2010	ACLR	13	Contralateral	4-12		↓	↓		↑	↓	
Oberlander et al., 2012	ACLD	13	Healthy	?	↑				↑	↓	↑
Oberlander et al., 2013	ACLR	10	Contralateral	6 -12	↑				↑	↓	↑
Xergia et al., 2013	ACLR	22	Contralateral	6-9	↔		↓	↓			
Roos et al., 2013	ACLD	21	Healthy	3-34	↔		↓		↑	↔	↑
	ACLR	23	Healthy	10-83	↔		↓		↑	↓	↑
Button et al., 2014	ACLD	22	Healthy	20		↔	↓	↑	↑	↔	↑
	ACLR	21	Healthy	26		↔	↓	↔	↑	↔	↔
Augustsson et al., 2006	Healthy	11	Muscle fatigue	na		↓	↓		↓		
Webster et al., 2004	ACLR	10	Shoe / bare foot	6 – 9			↓			↓	
Van der Harst et al., 2007	Healthy	9	contralateral	na		↔	↔		↔	↔	↔

Key: n = number of subjects, ACLD = Anterior cruciate ligament deficient subjects, ACLR = Anterior cruciate ligament reconstructed subjects, ↑ = increased in relation to comparator, ↓reduced in relation to comparator, ↔ not sig different from comparator, blank = not stared, na = not applicable. **Note:** differences in Webster et al. (2004) are significant but very small.

Several authors suggest that this is a knee avoidance strategy linked to quadriceps weakness (Orishimo et al., 2010; Xergia et al., 2013). Xergia et al. (2013) investigated mechanics and isokinetics and found asymmetries in both, however there was no direct comparison to facilitate understanding of the relationship. Oberlander et al. (2013) provided a direct investigation of the relationship between these parameters. They identified a large correlation (r squared = 0.78) between quadriceps strength and external knee flexor moment and suggested that the altered strategy is a compensation for the muscular weakness, although other motor control issues also require consideration. Augustsson et al. (2006) investigated SLHD landing strategy under conditions of quadriceps fatigue and demonstrated 20 % reduction in performance; however the only difference in landing strategy was reduced excursion at the hip. The use of EMG analysis has however demonstrated the presence of altered muscle recruitment and activation. Earlier onset of preparatory muscle activity in the quadriceps and hamstrings prior to initial contact has been described (Gokeler et al., 2010; Swanik et al., 2004), with no changes in the reactive activation during landing. This has led both these authors to conclude that the altered strategies are based on feedforward mechanisms.
Despite measuring both strategy and performance parameters none of the studies has directly investigated the relationship between them. However, the study of Orishimo et al. (2010) purposely measured subjects at the point at which they attained the LSI> 85%. Despite a mean of 93% (87-99) LSI alterations in landing strategy remained, suggesting that altered strategy exists despite passing performance standards.

The studies reviewed thus far have only considered the mechanics of the lower limb. However there is agreement that whole body mechanics are important in their effect on knee moments (Augustsson et al., 2006; Gokeler et al., 2010; Oberlander et al., 2012, Roos et al., 2013). Simulation studies have demonstrated that the position of the swing limb significantly influenced the magnitude of the horizontal GRF and its position relative to the stance knee (Gokeler et al., 2010). Also the large proportion of mass (45%) in the trunk means that trunk position and control is likely to have large effects on knee moments (Oberlander et al., 2012).
Oberlander et al. (2012; 2013) have used a full-body biomechanical model to assess SLHD landing in both ACLD (Oberlander et al., 2012) and ACLR (Oberlander et al., 2013) subjects.

These papers are unique in that they observed the same subjects before and after ACLR. Both groups were found to use the same strategy that fits the previously described knee avoidance, with reduced external knee flexor moment and increased moments at the hip and ankle. However the unique data including the trunk identified significant increase in forward Trunk Lean. The strategy resulted in a more anterior position of the centre of gravity and GRF vector which reduced knee moment and increased it at other joints. This is similar to the findings of Risberg et al. (2009) who identified increases in hip flexion angle during landing following a rehabilitation programme in ACLD subjects. However the Gokeler et al. (2010) sample had reduced hip flexion on the injured limb. Both studies had small numbers of participants (n = 13 and n = 10 respectively) and whilst it is quite possible this has sufficient power to detect significant differences, no evidence for this is presented. Hop distance was constrained at 0.75 x height which is a considerable distance but again prevents any meaningful association between performance and strategy from being identified.

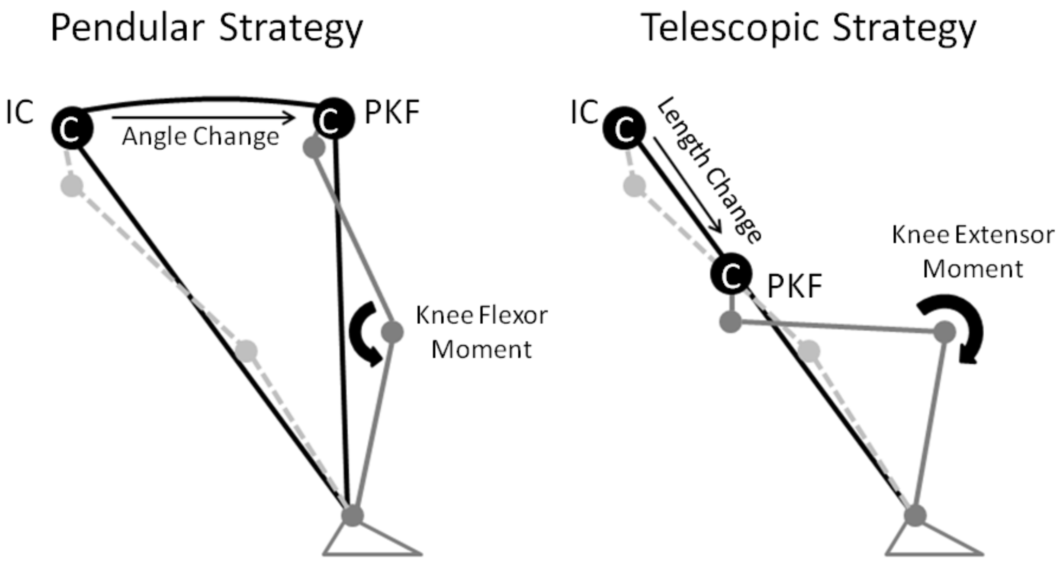
In order to look more holistically at the interaction of all of the body segments, complex biomechanical modelling using a Telescopic Inverted Pendulum (TIP) model has been applied to SLHD landing (Roos et al., 2013). The TIP model (Papa and Cappozzo, 1999, 2000; Mazza et al., 2006; Phillips and van Deursen 2008) simulates the body's centre of gravity (COG) as a telescopic segment which rotates about the ankle of the stance limb (Figure 2). Landing strategy is defined by the change in the length and angle of the TIP model, which can be classified as predominantly telescopic (large change in TIP length) or predominantly pendular (large change in TIP angle). Telescopic strategies put high demands on dynamic knee control and require high external knee flexor moments, whereas pendular strategies can be assumed to reduce the demand on knee control and extensor moment but increase demand at the ankle (Roos et al., 2013).

Using this model in a series of healthy, ACLD and ACLR subjects, Roos et al. (2013) demonstrated that ACLD subjects landed with a more upright posture and a more pendular strategy than healthy subjects who demonstrated a more telescopic strategy with greater knee bend. The ACLR group demonstrated recovery towards the healthy strategy but knee excursion and external flexion moments remained reduced. In contrast to the Oberlander studies, Roos et al. (2013) did not identify any significant group differences in Trunk Lean. However both groups provided evidence for reducing moments at the knee and increasing at the hip and ankle. Both groups provided robust evidence that landing strategy remains different from that of healthy subjects following ACLR.

This study has a reasonable sample with 21 ACLD and 23 ACLR subjects, although 5 ACLD refused to hop reducing the sample to 16. However, both groups have a wide spread of time from injury (3-34 months) and surgery (7-36 months) and whilst all subjects are known to have finished rehabilitation there is no mention of the classification of functional coping in the ACLD group. In contrast to Oberlander et al. (2012 and 2013) the hop distance was not constrained by Roos et al. (2013) and it is important to note that whilst the ACLD group showed significant reduction in hop distance, the ACLR group had regained performance close to healthy values.

The literature indicates that SLHD is an appropriately validated tests used to assess functional recovery following ACLR. Distance is used to measure performance usually expressed as a limb symmetry index. There is however evidence to suggest limitations of limb symmetry index as a primary outcome and recommendations that absolute distance and reference to healthy normative values should be further investigated. There is growing evidence that performance alone is inadequate and that assessment of landing strategy is an important factor which may provide important insight for rehabilitation. Knee avoidance strategies which reduce joint moments at the knee and increase at the adjacent joints are apparent in ACLD subjects, however the recovery of these strategies following ACLR requires further investigation. Since these strategies may represent modifiable targets for neuromuscular rehabilitation strategies, determining which are effective for both short term recovery of performance and long term knee health will be important. Further investigation of clinically applicable measuring tools are required to allow assessment during rehabilitation and further understanding of how rehabilitation may focus on resolving both strategy and performance parameters. The methods and data of this study will aim to fill these gaps in methodology and understanding.

Figure 2: The telescopic inverted pendulum (TIP) model; pendular and telescopic strategies are shown in relation to kinetics and kinematics of the lower limb joints.



Key: C = centre of gravity, IC = position at initial contact, PKF = position at peak knee flexion, straight arrows indicate direction of motion, curved arrows indicate direction and magnitude of moment.

Rationale for the thesis

ACL injury is common and leads to variable levels of functional stability, activity limitations and participation restrictions that can be described by the coper, adaptor, and non-coper classification. For those who proceed to ACLR, success has been defined as a symptom free return to pre-injury activity, however there are few studies using appropriate methods to assess this standard and further investigation is therefore required. The available literature presents a picture of variable outcome with incomplete recovery in all domains of the ICF. Rehabilitation provides an important stimulus for the motor control system to facilitate adaptations that improve functional stability and performance. There is agreement that criterion based rehabilitation, guided by functional movement tests are to be recommended following ACLR. However, recommended criteria are limited by the current understanding of functional recovery and the ability to assess it in the clinic. Therefore, the development and validation of novel clinically applicable measures of functional performance and movement strategy will enable the study of functional recovery before and after ACLR in the clinical setting. When used alongside a holistic approach to assessment in line with the WHO ICF and clinical significance criteria based upon healthy comparison it will be possible to make evidence based recommendations for functional movement criteria for the progression of rehabilitation on the basis of success.

Aims

The aim of this thesis was to study functional recovery following ACLR in a group of highly symptomatic non-coping ACLD subjects within a local NHS service.

Objectives

1. To develop clinically applicable methods for the assessment of strategy and performance during single leg squat and hop for distance in the clinical setting.
2. To define structure and function impairments, activity limitations and participation restrictions before and after ACLR.
3. To define the capabilities of functional performance measures, before and during rehabilitation following ACLR, to predict successful recovery at 1 year following ACLR.

Research questions

1. Do differences in functional performance and knee stability exist between patients waiting for ACL reconstruction and normal values?
   Null Hypothesis: There are no significant differences between the ACLD subjects and healthy subject data
2. Is functional performance and knee stability improved 1 year following ACLR?
   Null Hypothesis: There are no significant improvements in functional performance and knee stability 1 year following ACL reconstruction.
3. Do differences in functional performance and knee stability exist between patients 1 year following ACL reconstruction and normal values?
   Null hypothesis: There are no significant differences in functional performance and knee stability in subjects 1 year following ACLR and healthy values.
4. Can success following ACLR be predicted using functional performance measures taken before or during rehabilitation after ACLR.

Methods

The methods section will describe the clinical setting in which the research was conducted and the pathway of care including the intervention and clinical review service in which data was collected. The longitudinal observational methodology is then described along with the recruitment and consent procedures. The outcome measures are described next, with the procedures applied for data collection and processing. Finally, details of the statistical and clinical significance analysis methods are presented for each of the four research questions.

The setting

Aneurin Bevan University Health Board (ABUHB) has a catchment of approximately 570,000 people and is spread across the eastern side of the south Wales valleys. At the time of conducting the study ABUHB had no specialised provision for screening of acute knee injuries beyond the emergency department. As a result a majority of the ACL injured patients presenting to the Trauma and Orthopaedic department do so following general practice referral having failed to recover. The population was therefore expected to represent a highly symptomatic, non-coping group with delayed diagnosis and poor functional recovery prior to surgery.

The ACLR review service

The study took place within an existing service for the clinical review of ACLR patients within ABUHB. Since its introduction in 2003, this service has provided a package of pre and post-operative assessment and intervention as recommended by best practice consensus statement from British Orthopaedic Association (BOA), the British Association for Surgery of the Knee (BASK) and the British Orthopaedic Sports Trauma Association (Allum et al., 2001). The standard process is to invite all patients to attend for one pre-operative and five post-operative appointments (at 6 weeks, 3, 6, 12 and months following surgery). Following clinical assessment and collection of outcome measures, appropriate investigations or interventions are instigated. There was no additional clinical time allocated to the study, the study was therefore designed to be completed within the constraints of the existing model.

Specifically, the time allocated to each review could not be changed and it was therefore necessary that all data could be collected within the 30 minute time allocation.

The Intervention

The intention of the study was to investigate the outcome of current or typical clinical practice following ACL reconstruction (Xergia et al., 2013; Paterno et al., 2010) and therefore the intervention was not adapted in any way for the purposes of this study. The surgical intervention used a 4 strand semitendonosis gracillus (STG) autograft taken from the ipsilateral leg, fixed into anatomic oriented bone tunnels using Endobutton and Biolok screws. A few subjects had fixation with tape locking screws. All surgery was conducted at the orthopaedic surgical unit at St Woolos hospital, Newport, UK. The post-operative rehabilitation programme follows guidelines that were updated in 2009 (Appendix 1). This is brace free rehabilitation that encourages early weight bearing and knee ROM within tolerance and encourages early integration of functional exercise. The guideline is not prescriptive and encourages individualisation of the rehabilitation programme to the goals and capabilities of the individual. The service encourages a mix of clinic based rehabilitation either on a one to one basis or in groups and home exercise, according to the needs and abilities of the subject. Whilst there are gym facilities in each participating rehabilitation department, they are limited to a few pieces of cardiovascular equipment (cycle ergometers, cross trainers and treadmills), and some free exercise equipment such as balance boards and Swiss balls. Resistance training equipment is limited to a few light dumbbells (<10kg).

Study Design - Longitudinal methodology

The longitudinal, observational nature of the clinical service was utilised to collect prospective, longitudinal data on the same subjects at the time points described. Since there was an interest in recovery during the early post-operative period, resources to provide one additional appointment was negotiated; the 6 week appointment was replaced with appointments at both 4 and 8 weeks following surgery, increasing the post-operative data to 5 occasions, and a total of 6 longitudinal data points.

Timing of data collection

The aim was for data to be collected from each participant at the 4th, 8th, 12th, 26th and 52nd week following surgery, which would constitute, 28, 56, 84, 182 and 364 days following surgery respectively. Since the review clinic runs once a week on a Wednesday, there would be a theoretical maximum of 4 days either side of the target number days from surgery (i.e. subjects would be seen 24-32, 52-60, 80-88, 178-186 and 360-368 days following surgery). Inevitably some participants will not be available to meet this tight schedule and therefore the nearest possible date was accepted and was dealt with during the analysis.

The pre-operative data formed the basis for the identification of differences between ACL injured subjects with healthy in question one. The pre-operatively data was then compared to the 12 month data in a same subject pre-post comparison to identify changes to answer question two. A final comparison between the 12 month and healthy data was used to define recovery and residual deficits in order to answer question three. Finally the entire pre and post-operative longitudinal data set was used in the development of regression models to identify predictors of outcome 12 months after surgery.

Study Participation

Recruitment

All patients that were awaiting primary STG ACLR that fulfilled the inclusion and exclusion criteria were identified at the preadmission clinic and invited to the pre-operative assessment within 6 weeks of surgery. They were informed of the research and invited to participate following the written and verbal processes agreed by the South East Wales Research Ethics Committee (SEWREC) Panel D (Appendix 2). Subjects that consented were recruited if they met the following criteria:

Inclusion Criteria: Adult (over 18 years), listed for a primary unilateral autologous hamstring graft ACLR.

Exclusion Criteria: Previous ACLR, previous knee surgery, unable to fulfil follow-up requirements, pre-existing physical limitation affecting gait or lower limb activity, inability to understand the English language.

Adverts for healthy subjects were circulated in paper and electronic format through the clinical and student networks at ABUHB and Cardiff University School of Healthcare Sciences (SOHCS) in accordance with the SEWREC permissions. Subjects were recruited from those that responded if they met the following criteria:

Inclusion Criteria: Adult (over 18 years), normal knee with no history of injury or surgery.

Exclusion Criteria: History of lower limb injury or surgery, physical limitation affecting gait or lower limb activity, inability to understand the English language.

Informed consent

All potential participants received the written and verbal information as outlined in the SEWREC approved protocol (Appendix 3). Written informed consent was gained at the pre-operative assessment, prior to any data collection (Appendix 4).

Sample size calculation

Group comparisons in the first three questions were based upon t-tests and a power analysis was completed to inform recruitment. Whilst data regarding changes in gait parameters following ACLR is scarce, Knoll et al. (2004) provide sufficient data for step length to calculate differences between healthy, ACLD/ACLR that are relevant to the power of the current study. The smallest mean difference occurs between healthy and ACLD subjects, representing a standard difference of 1.02 (513.3-478.1 / (26.6+42.5/2) = 1.02). With a power of 0.8 and an alpha level of 0.05 for analysis with a t test, a minimum of 15 subjects was required (Faul et al., 2007). Allowing for a drop-out rate of 50%, a minimum of 30 subjects was required. A group of 60 non-injured controls matched for age and activity level were recruited from volunteers at Cardiff University and ABUHB, allowing for a 2:1 analysis with the related t-test, and clinical significance comparison with the standard mean.

In order to answer question four a prediction model was determined using regression analysis. The number of subjects required to maintain power of a regression analysis is dependent upon the number of variables that will be entered into it, however there is no consensus standard for this. Peduzzi et al. (1996) proposed a simple rule of ten outcome events for each predictor variable that is entered into the model, which has been widely adopted in the literature. Recent modelling studies have suggested that this rule may be too conservative and could be relaxed (Vittinghoff and McCulloch, 2006) to include more variables. A maximum of 10 variables were anticipated and therefore even using the conservative standard of Peduzzi et al. (1996), 100 subjects would be more than sufficient for the regression modelling required in this study. Data of attendance at the ACLR review service in the year prior to the study (2008/9) showed that 91 subjects would have been eligible for the study with a drop out at 1 year follow up of 20%. Therefore, even with a 50% recruitment there was considered sufficient potential to recruit 100 subjects over a 2 year recruitment period.

Outcome measures

Outcome measures were selected to fulfil the aim of assessing recovery of functional performance and knee stability against the criteria defined by Lynch et al. (2015). Clinically applicable outcomes which could be utilised within the constraints of the research setting were selected from each domain of the WHO ICF; structure and function, activity and participation. Several aspects of the patient pathway (time to diagnosis, time to surgery, prehabilitation) were also considered important as possible predictors.

Pathway Data

Several characteristics of the individual and the care pathway were of interest as potential predictors for analysis on question four. The following data set was therefore collected from electronic patient records available through the clinical workstation within the ABUHB. Where clinically recorded information was not sufficiently accurate (e.g. date of injury) clarification was sought from the subject.

- Demographics – age, gender, weight and height.
- Date of injury.
- Mechanism of injury (contact or non-contact).
- Date of surgery.
- Rehabilitation between injury and surgery.

Structure

The structure of the knee following injury and surgery was defined by the findings from pre-operative imaging and examination of the knee at surgery. The following data was collected from the electronic patient record:

- MRI findings provided details of injured structures.
- Examination under anaesthesia (EUA) findings: ligament laxity; Lachmans (Hurley and McGuire, 2003, Ostrowski, 2006), pivot shift (Hoshino et al., 2007), dial (Veltri and Warren, 1994), valgus, varus stress tests. All tests are scored I = no displacement II = displacement but with solid end feel III = displacement with open end feel (Lubowitz et al., 2008).
- Surgical findings: Chondral injury was classified as present or not with the location (medial lateral or PFJ) and International Cartilage Rating System (ICRS) grade 0 -4 (Britberg et al., 2003). Meniscal injury was classified as present or not with the location (medial, lateral or PFJ), and intervention (repair or resection).

Functional stability

The Lysholm knee score has previously been used as separate subscales (Briggs et al., 2009) and the instability subscale was therefore adopted as the measure of functional instability in this study. This allows the individual to describe functional instability at six levels on an ordinal scale, from “no giving way” to “giving way at every step”.

Participation

A systematic review of patient reported methods to assess participation has been presented in the literature review (Letchford et al., 2012). Four commonly used PROMs were identified; however there was a lack of evidence supporting appropriate measurement properties in the ACLD and ACLR populations. Recommendations were made to provide complete a comparative analysis of the identified tools to establish recommendations for a preferred PROM in this study population. The longitudinal nature of this study lent itself to such a study and this was therefore conducted (Letchford et al., 2015). The following section will provide a brief description of the methods used; further detail is available in the published paper.

Pilot study 1: Assessing participation in the ACL injured population: Selecting a patient reported instrument on the basis of measurement properties.

Since the development of Psychometrics as a methodological discipline there has been debate in the literature regarding terminology and methods. Significant advances towards resolving this debate have been made by the COSMIN (COnsensus-based Standards for the selection of health Measurement INstruments) initiative (Mokkink et al., 2010a, 2010b, 2010c). This group of biostatisticians have applied Delphi methods to gain international consensus and publish a standardised taxonomy, terminology and methods for the assessment of measurement instruments. Consensus was achieved (>69% agreement) for the structure of the taxonomy and for all of the design and statistical requirements.

The COSMIN consensus guideline was therefore followed to conduct a study to compare the measurement properties of the four identified participation PROMS (Tegner, CSAS, IKDC and Marx scale) and make recommendations for research and clinical practice applications. A comprehensive assessment of reliability, measurement error, content validity, construct validity, responsiveness and interpretability using the recommended methods was used. Detailed information on the methods is available in the published article; Letchford et al. (2015). The four participation PROMS (Tegner, CSAS, IKDC and Marx scale) and a seven point global rating of change score (GRCS) was included to act as an anchor for change that would be required for the investigation of minimally important difference (Norman et al., 2001). The study identified the Tegner scale as the preferred PROM in this population and this was therefore used in the analysis of questions 1-4.

Knee Function

The IKDC and Lysholm scores previously described in the literature review were included within the study protocol at each attendance. The Lysholm score is presented as a raw score out of 100, the IKDC SKF is converted to a percentage score (Irrgang et al., 2001). Pain is an important limiter in function activity and participation and whilst both functional scores contain a pain subscale pain a separate measure was considered important. The standard 100mm Visual Analogue Scale (VAS) has been demonstrated to be a valid and reliable method of measuring pain intensity (Johnson, 2005) and was therefore included in the study protocol. Several authors have tried to classify pain intensity on VAS (Collins et al., 1997; Hawker et al., 2011). Collins et al. (1997) provide data from 1080 patients who classified pain intensity on a VAS and an ordinal scale of mild moderate and severe. Using the 85th percentile they recommend that VAS score over 30 mm be classified as moderate pain and over 54 as severe pain. This classification was adopted for the descriptive analysis of pain severity in this study.

Activity

Functional testing using gait, SLS and hop for distance have been described in the literature review as potentially important milestones in the recovery process. Motion analysis was considered a useful method by which both performance and strategy measures could be developed and analysed. 2D digital video offers a method by which this data can be collected within the restraints of clinical practice. Whilst skin markers are commonly used in these methods, this can be time consuming and impractical for clinical applications and so the development of a system without the need for skin markers was explored. This approach is novel and required investigation of reliability and validity of the method used to record the movements and parameters of interest. Existing understanding of 2D DV methods and the processes of developing the new methods and tools are now described.

Clinical motion analysis using 2D digital video

There is a growing body of literature supporting the reliability, validity and clinical application of 2D video for motion capture and analysis (Steffen et al., 2014; Mclean et al., 2005; Herrington and Munro, 2010; Ugbolue et al., 2013; Clarke and Murphy, 2014; Gwynne and Curran, 2014). Several studies have assessed the use of various 2D DV systems for the assessment of temporo-spatial characteristics of gait (Ugbolue et al., 2013; Reid et al., 2005; van Deursen et al., 2001) and despite slightly different methods they consistently demonstrate appropriate levels of reliability. Reliability for gait velocity is reported at ICC 0.99 by van Deursen et al. (2001) and 0.89 by Reid et al. (2005), Ugbolue et al. (2013) report ICC>0.94 for all temporo-spatial parameters of gait. A majority of the literature using these methods for kinematic analysis has focussed on the assessment of frontal plane knee angles during various functional tasks. Both Mclean et al. (2005) and Steffen et al. (2014) have compared 3D motion analysis and 2D digital video (2D DV) analysis methods for measuring the frontal plane projection angle (FPPA) and demonstrated that both methods gave similar patterns of movement. More recently Gwynne and Curran (2014) provided a direct comparative analysis of FPPA from simultaneously captured 3D and 2D data. They have demonstrated a high correlation (r = 0.64 to 0.78, P <0.001) between the two methods which supports the use of 2D methods for clinical applications. Furthermore they demonstrated that reliability was high (ICC>0.71) for the 2D DV system. Table 11 summarises the high level of reliability that is reported in recent studies using 2D DV analysis for lower limb and trunk kinematics during functional tasks. Importantly these measures have greater reliability than clinical classification systems for motion analysis (Bruunkreef et al., 2005; Von Porat et al., 2008).

Table 11: Reliability of 2D DV analysis of joint ROM reported in the literature

Study	Reliability (ICC)			
	FPPA	Hip	Knee	Trunk
Clarke and Murphy, 2014			>0.93	
Gwynne and Curran, 2014	>0.71			
Dingen et al., 2013				>0.98
Stensrud et al., 2012	>0.92			
Munro et al., 2012	>0.72			
Goetschius et al., 2012			>0.99	
Norris and Olsen, 2011		>0.79	>0.91	
Poulsen and James, 2011	>0.88			
Herrington and Munro, 2010	>0.90			
Levinger et al., 2007	>0.88			
Cronin et al., 2006			>0.89	

Key: ICC = intraclass correlation coefficient

Most of these studies utilise a skin marker system and there has been debate in the literature about the use of marker less motion capture systems (Ceseracciu et al., 2014; Goetschius et al., 2012; Bartlett et al., 2006). Bartlett et al. (2006) have demonstrated significantly greater variability in the measures obtained using marker less digitisation when compared to a marker based system. Whilst the small differences in this study suggest that these systems are not sufficiently accurate to measure the small amounts of stride to stride variability in kinematics, they do not suggest that the system is not sufficiently reliable for one off measures of kinematics to define a motion strategy. Two methodologies without a marker system were identified. Goetschius et al. (2012) measured knee flexion in the sagittal plane by placing the arms of the digital goniometer along the anterior aspect of the thigh and leg. Whilst the study demonstrated excellent reliability (ICC = 0.997), it was performed by only 2 raters on just 10 sets of data. Stensrud et al. (2011) adapted the FPPA (Willson et al., 2006, 2008) to use without markers by estimating joint centres. The study demonstrated good intratester reliability (ICC=0.92) with measurement error of 3.3 degrees, however 30 day test retest reliability was lower (ICC 0.57 to 0.84). Just 20 data sets were used for the intratester reliability and 18 for the test retest.   A more robust analysis of marker less methods was required and two pilot studies were therefore conducted.

Pilot Study 2: Reliability of sagittal plane knee motion using SiliconCoach

The first study assessed test-retest and interrater reliability of sagittal plane knee flexion and FPPA extracted from a marker less system on DV clips using SiliconCoach (SC) video analysis software. DV clips from a convenience sample consisting of the first 15 ACLD subjects to complete the longitudinal data collection procedure with full data sets were included in the analysis. Still screenshots (Jpeg files) were extracted from both the injured and non-injured legs of each subject at each attendance, coinciding with the estimated peak flexion angle of the first hop landing. These files were entered into a SC presentation and was analysed by 2 independent researchers (RL, KB) at 2 time intervals at least 2 weeks apart (De Vet et al, 2012). Each researcher was instructed in the standardised data extraction procedure and provided with written guidance and an opportunity to practice.

The instructions were:

For each JPEG provided, use silicon coach to create a goniometric measurement of FPPA using the following process:

- For each video clip provided, use silicon coach to measure the knee flexion angle.
- Click on the zoom feature and set to x3.
- Click on the angle tool.
- Click on the anterior aspect of the ankle.
- Move the crosshatch towards the knee so that the line falls along the anterior border of the shin.

- Click anteriorly to the knee such that moving the cross hatch towards the hip leaves the first line along the anterior border of the shin and produces the second line along the anterior border of the thigh.
- Click on the proximal portion of anterior border of the thigh.
- Document the angle in degrees.

Flexion angle is then calculated as follows:

- As SC always measures the angle clockwise, the left leg will be a correct measure but a conversion is required for the right leg using Equation 1.
- **Equation 1:** Right leg flexion = 360 – x

Reliability was assessed using ICC for consistency with a mixed model (Karanaiolas et al., 2009; De Vet et al., 2012). Agreement was assessed with Bland and Altman plots (Bland and Altman, 2010) with 95% limits of agreement (LOA) as detailed in Equation 2. Standard Error of Measurement (SEM) was calculated using the methods described by de Vet et al. (2012) as detailed in Equation 3.

Equation 2: LOA = mean difference ± 1.96 (standard deviation of the difference)

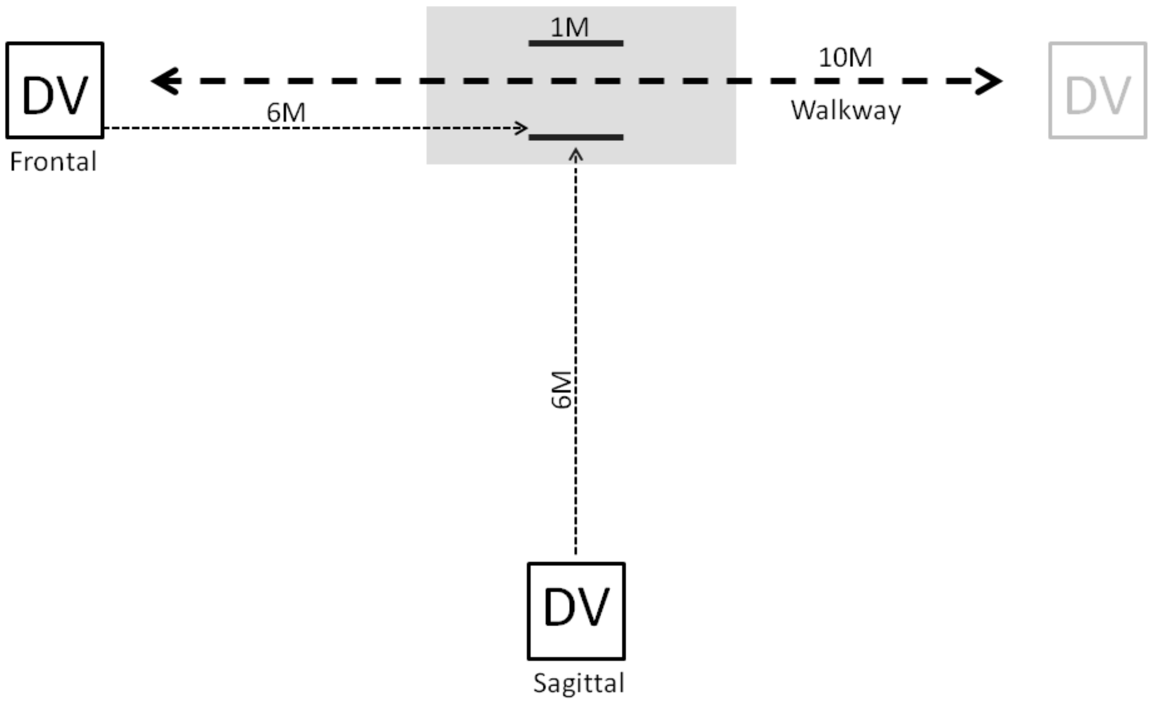
Equation 3: SEM = SD x square root of 1-r where r= reliability co-efficient or ICC.

The second study was a much more comprehensive assessment of the ability to locate landmarks using a markerless system that was performed within a study of the measurement properties of a new tool for measuring landing strategy during hop for distance. The methods for this study are detailed in a further section (Pilot Study 3: A novel clinical approach for assessing hop landing strategies: a 2D telescopic inverted pendulum (TIP) model) and are available in the publication (Letchford et al., 2014).

Motion Capture

Motion capture for all elements of this study was performed using a biplane set up with 2 digital video cameras (See Figure 3). The DV cameras (Canon Legira HFR16, Canon UK Ltd, Surrey, UK) were placed on tripods (Sony, Sony Europe Ltd, Surrey, UK) at a height of 1m and distance of 6m from the centre of the data collection volume in both the frontal and sagittal plane. A 10 metre walkway was available for walking trials with data collected from the central region of this. Two sticks marked at 1m were used to calibrate the digital images for distance (See Figure 4 and 5). This method has been proven to be a valid and reliable method of obtaining accurate measures of functional tasks (Von Porat et al., 2008). The DV clips were transferred to encrypted, password protected digital storage for analysis.

Figure 3: Schematic representation of the motion capture set up. Video cameras (DV) are placed 6m from the data collection volume (shaded) containing two 1M calibration sticks, in the frontal and sagittal plane. A 10m walkway is available for execution of task



Activity tasks

The selection of three activities (gait, single leg squat and hop for distance) and the anticipated hierarchy have been presented in the literature review. Well defined and consistent instructions were applied to reduce any interpretation differences in what the task is about (see below), however individual variations in this cannot be ruled out. Whilst cues were given for performance, i.e. “comfortable performance” in gait and “maximal performance” in hop and squat, no instruction was given regarding strategy which was purposely unconstrained so that self-selected strategy could be assessed.

None of the activity measures included an opportunity to practice. This was necessary to complete the data collection within the allotted clinical time and was therefore considered to reflect the use of functional tasks in the assessment of movement dysfunction within the clinical setting where limited time is available. Task performance is known to change with practice (Bolga and Keskula, 1997) and it could be suggested that some of the measures are therefore conservative estimates of performance. However, all subjects were introduced to the tasks at the pre-operative assessment and it was expected that the tasks were common components of post-operative rehabilitation sessions and could therefore not be considered novel tasks at that point in time.

Instructions given to participants were:

Gait: Subjects were instructed to “Walk at your comfortable speed” along a 10m runway between calibration sticks before turning and returning down the runway. This was repeated three times.

Single leg squat: Subjects were instructed to “Stand on one leg with the toes of the other leg resting on the floor behind you, on the command to start, lift the back foot, then bend the weight-bearing knee as far as you feel able before returning to upright, repeat this as many times as you can” and “There are 2 rules, bend the knee as far as you can and repeat it as many times as you can”. This was performed once, if a subject lost balance (placed contralateral limb on the floor) before the second repetition was complete a further attempt was allowed.

Hop for distance: Subjects were instructed to “Stand on one leg, hop as far as you can and land on the same leg. You must hop as far as you feel you can whilst maintaining a stable landing” and “There are 2 rules, hop as far as you can and maintain a stable landing”. This was repeated until 3 repetitions within the rules were observed.

Data Extraction and Processing

For all elements of the study data was extracted for performance (gait velocity, squat depth and hop distance) and strategy (step length and cadence in gait and landing strategy for hop) from the DV clips. SiliconCOACH Pro (version 7) video analysis software (Silicon Coach, Tarn group limited, PO Box 33, Dunedin, New Zealand) was used to display and synchronise the sagittal and frontal plane DV clips. The software enables the video to be viewed frame by frame in order to select the frame. The two videos were synchronised at the frame where ground contact occurred. The synchronised clips were then scanned frame by frame to identify the required phase of each activity; these were three consecutive heel strikes in gait, at peak knee flexion in single leg squat and at toe off, initial contact and peak knee flexion in hop landing. Still images of these frames were then extracted in Jpeg format (Figure 4), ready for further analysis. These images were loaded into bespoke motion analysis software written in MATLAB (Mathsworks, Matrix house, Cambridge, UK) by Prof R.W.M. vanDeursen. These programmes, DVGait and DVHop, have previously been described by Button et al. (2005) for the extraction of data from digital video for temporo-spatial characteristics of gait and hop distance. The reliability of this system for calculating gait velocities has been found to be high, with an inter-tester reliability of ICC=0.99 and reliability between assessors and an optoelectric timer of ICC=0.98 (van Deursen et al., 2001). In both programmes the two 1m sticks were used to calibrate distance and frame times provided temporal data. The heel of the shoe was used to identify the location of heel strike and the toe for take-off and landing in hop (Figure 5). The software then calculated the outcomes of interest and saved them in files that were not accessible to the investigator. Further MATLAB software was used to access these files and to compile spreadsheets and plots for inspection only after all data collection and extraction was completed. This ensured the chief investigator was blinded to results throughout the data collection period.

Silicon coach was used in the extraction of kinematic data for single leg squat (Figure 6) using the method described by Goetschius et al. (2012), a detailed description of which is given on page 120; Pilot Study 2: Reliability of sagittal plane knee motion using SiliconCoach. The pilot conducted in this study to assess sagittal knee flexion in hop supported the use of this methodology without the use of markers.

Figure 4: Example of Jpeg stills extracted during gait using Silicon Coach. Three consecutive heel strikes are shown with the frame time displayed in the top left.

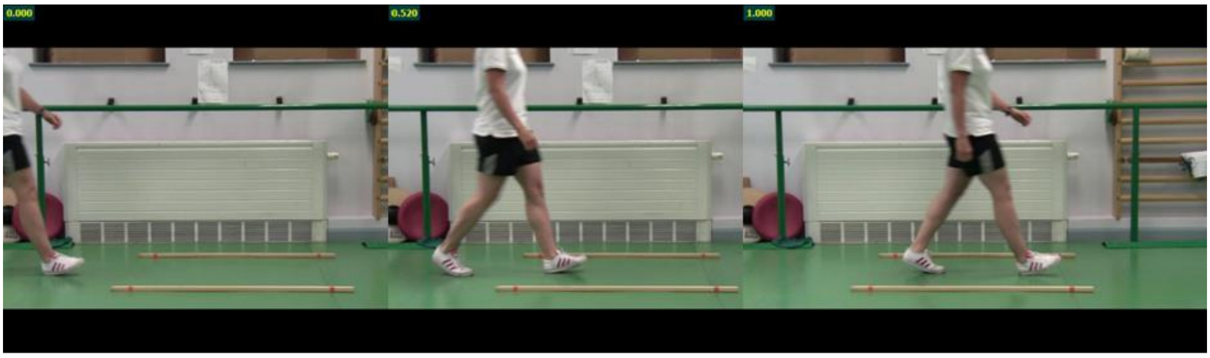


Figure 5: Screenshot of DV Gait software. The orange marks on the wooden sticks are used to calibrate the data collection volume on the floor. A cross hatch is used to identify the location of heel strike. The frame times are pre loaded and displayed at the top.

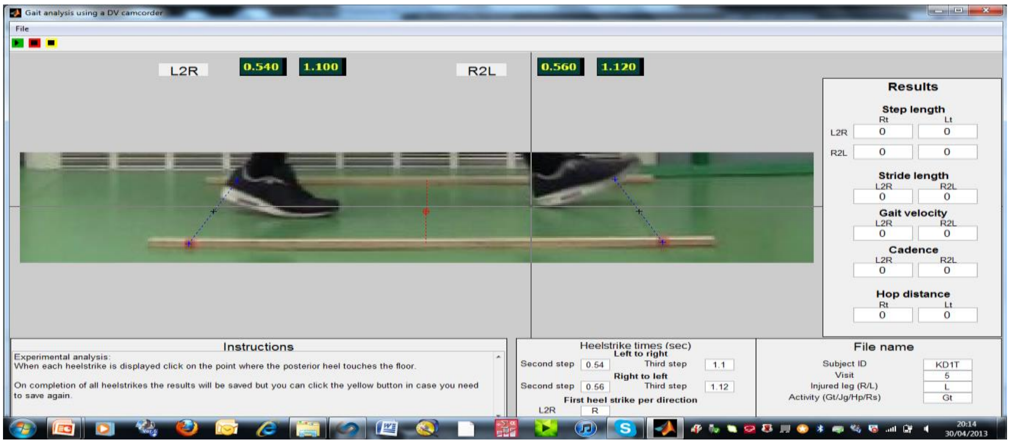
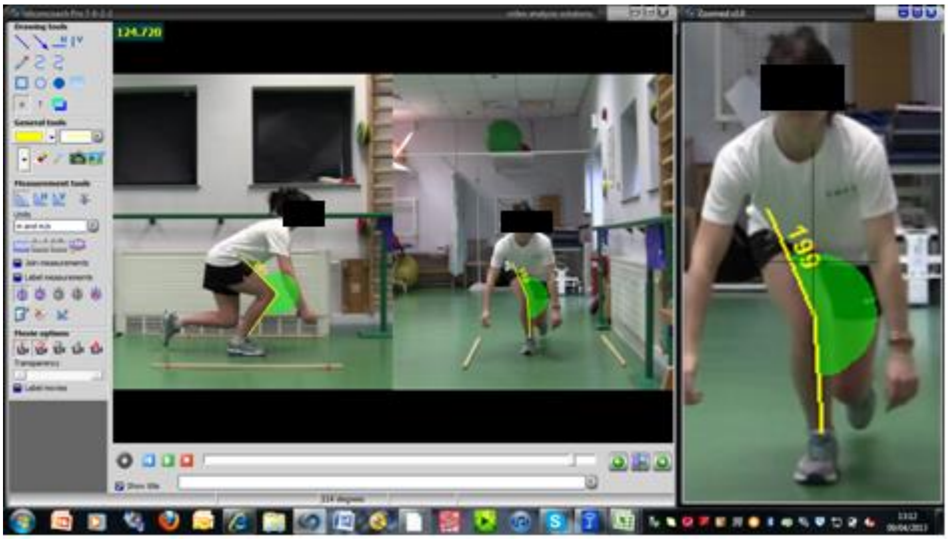


Figure 6: Screenshot from Silicon coach assessment of knee ROM. The zoom function is used to improve identification of anatomic landmarks.



Pilot Study 3: A novel clinical approach for assessing hop landing strategies: a 2D telescopic inverted pendulum (TIP) model.

A new method (DVTIP) to assess hop landing strategy using sagittal plane kinematics and a telescopic inverted pendulum model (TIP) was developed. The DVHop MATLAB programme was adjusted to include location of estimated joint centres for the major joints of the limbs, head and spine in the sagittal plane (Figure 7). The digital coordinates of these locations were then entered into algorithms based upon the anthropometry data of Winter (2009), to produce an estimate of the location of the COG for each body segment and subsequently for the COG of the body using a weighted average. The TIP model was then applied using the ankle centre as the distal fixed point and the COG as the mobile proximal segment. The angle (formed posterior to the direction of travel and from the horizontal) and length of the TIP model (distance from ankle centre to centre of mass) is used to define landing strategy (Figure 8) on a spectrum between a predominantly pendular strategy which is dominated by angle change and a telescopic strategy which is dominated by length change (Figure 9).

2D TIP data were extracted from saggital videos of hop for distance landing. A convenience sample of the first 30 healthy and 30 ACLD subjects (data extracted from pre-operative and 6 months post-operative attendances) were included. Sample size calculation on the basis of previous TIP data from van Deursen and Phillips (2006) indicated that with alpha of 0.5 and power 0.8, 26 subjects were required to detect changes in TIP parameters. Three independent raters extracted 2 repeated measures at least 24 hours apart. A comprehensive analysis of the measurement properties of the new tool was completed following the recommendations of the COSMIN group (DeVet, et al., 2012) which have previously been described. This included reliability (ICC agreement), SEM, construct validity (hypothesis testing), known groups validity (group differences between ACLD, ACLR and healthy) and responsiveness (magnitude and direction of group differences). This study has been published and further detail of methods is therefore available in the paper (Letchford et al., 2014).

Figure 7: Screenshot from DVTIP; Anatomical landmarks are located and the programme calculates an estimation of the COG location and the length and angle of the TIP model using the ankle centre as a fixed distal point.

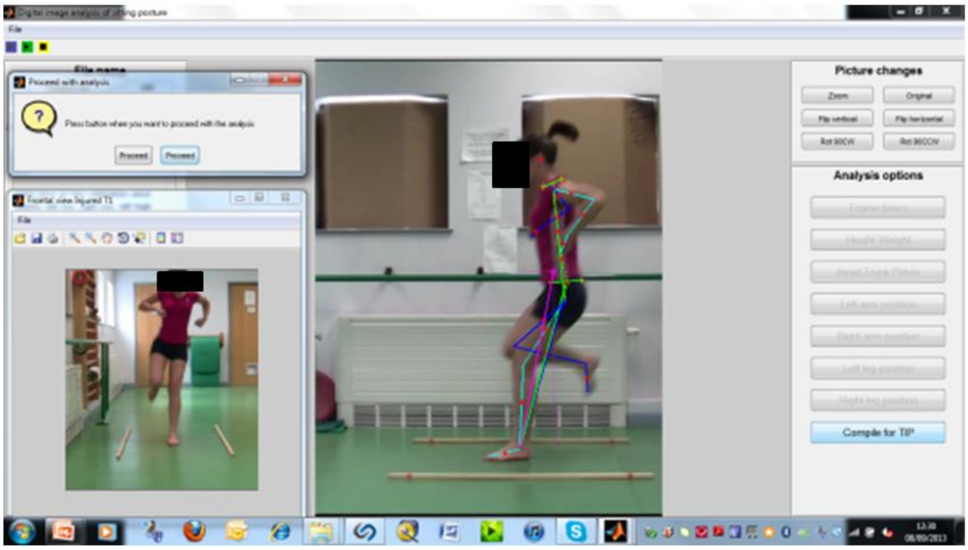


Figure 8: Diagram showing the parameters of the TIP model.The TIP length is the distance between the ankle centre and centre of mass with the TIP angle measured from the horizontal posteriorly to the direction of travel.

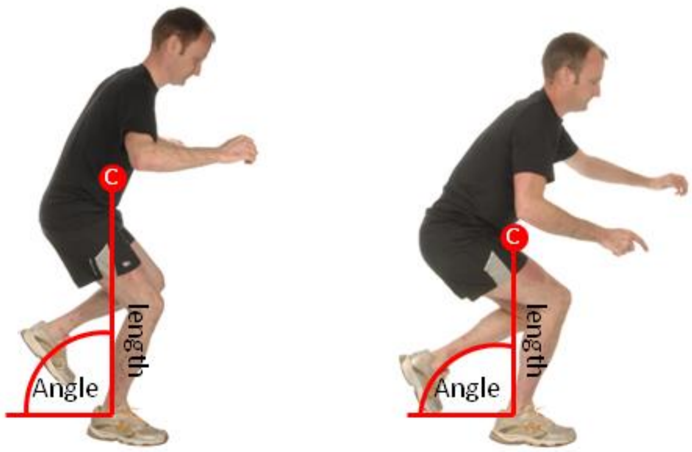
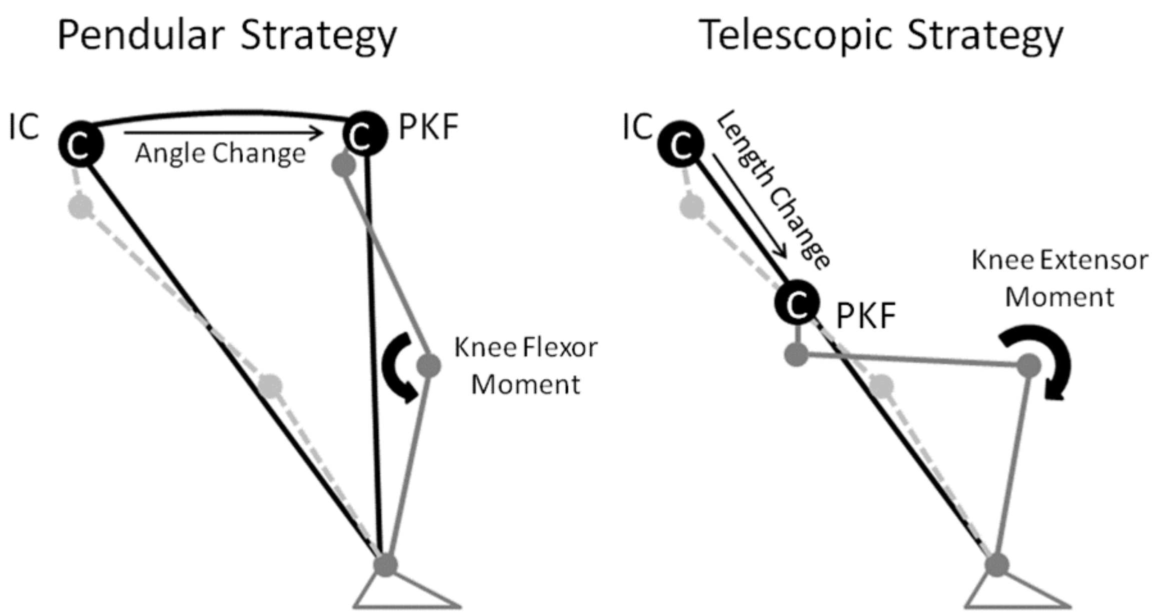


Figure 9: Schematic to demonstrate the telescopic Inverted Pendulum model applied to measure excursion of the centre of gravity (C) between initial contact (IC) and Peak Knee Flexion (PKF) during hop landing. The extremes of strategy, pendular and telescopic are displayed.



Data collection and processing

The study was completed within the clinical setting in ABUHB with the researcher fulfilling both clinical and data collection roles. This had the advantage of access to clinical data and the disadvantage of a risk of bias. Several important processes were therefore adopted to minimise the risk. Increasing knowledge over the period of study will undoubtedly have influenced the thinking and therefore the interaction with the patient, regardless of attempts not to make changes to practice. However, the data available to the investigator at interactions with the patient were limited to the clinical elements (PROMS and clinical examination) that have always been available, representing standard practice. The investigator was blind to all of the motion analysis during the data collection and extraction phases. The primary concern during data extraction was in maintaining the reliability of the methods that were established in the pilot studies. Interim checks of the data were carried out by third parties, so that the investigator only saw data patterns after data processing was complete. Custom MATLAB software was written to extract the data from the files and present it in Excel spreadsheets that could then be transferred into SPSS for statistical analysis.

Statistical Analysis

Missing data

Typically in longitudinal studies a plan to appropriately manage missing data is required. Firstly, strategies described by Hardy et al. (2001) and Sharp and Hamilton (2001) were adopted to minimise non-attendance. Each subject was given comprehensive information about the purpose of the clinical review service and research using the approved written documentation. All appointments were arranged either in person or over the phone and confirmed in writing within 2 weeks of the appointment date. Interference with other activities was minimised by offering times convenient to the individual. Secondly, a statistical strategy was generated to describe, assess and deal with any missing data that arose. There is no consensus on what constitutes a problematic amount of missing data within longitudinal studies; recommendations vary between 5% and 20% (Schlomer et al., 2010). However, the more important consideration is the effect that the missing data has in terms of potential bias and loss of power (Schlomer et al., 2010). An important step is to test the assumptions of missing completely at random (MCAR) missing at random (MAR) and missing not at random (MNAR) described by Rubin (1976). If the MAR/MCAR assumptions are supported modern imputation methods can be used to deal with the missing data issue (Schlomer et al., 2010; Graham, 2009). Whilst it is possible to test the MCAR assumptions using Little's test (Little, 1988), the MNAR assumption cannot be empirically tested. Missing data assumptions must therefore be justified through logical argument (Enders 2011) taking into account differences in baseline characteristics, the pattern and theoretical cause of missingness (Graham, 2009). The principles outlined by Graham (2009) and Schlomer et al. (2010) were applied in this study. The missing data module in SPSS was used to describe the distribution and pattern of missingness in the data set. The mechanisms for why the data was missing were identified and described. Little's MCAR test was performed. The effects of missing data at the final follow up was investigated by plotting the primary outcome variables over time for those with and without missing data (Heddecker and Gibbons, 1997) to identify any apparent differences in trajectory over time. Following the methods described by Schlomer et al. (2010), dichotomous variables (non-attendance and refusal to perform activity tests) were dummy coded prior to making assessments of relations (t tests and biscerial point correlations) with other variables that test the MAR assumption (Schlomer et al., 2010). Support for the MCAR/MAR assumption in each of these was required to proceed with imputation methods.

Imputation is one of several modern methods for analysing data sets with MAR or MCAR missing data. Whilst full information maximum likelihood (FIML) methods are often preferred (Howell, 2008) they were considered too complex for application in this study. Whilst multiple imputation (MI) might be considered the preferred option, at the time of analysis there was no recognised method for pooling parameter estimates for the statistical tests applied in this study and therefore expectation maximisation (EM) imputation was considered the most appropriate solution (Shafer, 1999; Graham, 2009). Primary and auxiliary variables for inclusion in the EM imputation model were identified through analysis of differences between those with and without missing data and correlation analysis, all variables with a correlation of $r>0.4$ were included (Collins et al., 2001; Graham, 2009). Each of the primary variables was imputed in a separate model. In order to preserve the longitudinal nature of the data, variables were entered into the missing data model in time order, with the complete baseline data first and ordered by the most useful variables (highest correlation). The EM algorithm was applied using a normal model with sufficient iterations to achieve convergence.

Data distribution

The reliance of parametric tests on the assumption of a normal distribution has been well documented (Field, 2009) and it is frequently suggested that when this assumption is violated a non parametric test should be preferred. However recent investigation has demonstrated that parametric tests are often robust to violations of the normal distribution assumption (Stonehouse and Forrester, 1998; Norman, 2010; Schminder et al., 2010) and that the addition of further robust testing procedures to parametric tests may be preferable to non-parametric alternatives (Krishnamoorthy et al., 2007; Cribbie et al., 2011). Trimming of means with replacement of outliers and transforming data to better represent the normal distribution with the use of robust methods such as bootstrapping are therefore recommended (Wilcox et al., 2013) and were adopted in the analysis of this study data. Kolmogorov-Smirnof test (K-S), Q-Q plots, histograms and distribution statistics were calculated for the standardised residuals from general linear model (GLM) procedures. When these methods did not support the normality assumption, outliers (z score > 3) were trimmed to the next highest / lowest score +/- 1 and transformations using square root and Log 10 were explored (Field, 2009). Normal distribution and equality of covariance were further assessed at each analysis and when these assumptions were not supported, robust bootstrap methods were applied (Field, 2009). In these instances bootstrap means, differences and significance are presented.

Presentation of data

Tables are presented using mean and standard deviation (SD) for scale data, median and interquartile range (IQR) for ordinal data. Statistics are presented with p values and effect sizes, mean difference and 95% confidence intervals. Statistically significant findings ($P<0.05$) are highlighted in tables by shading in greyscale.

Questions 1, 2 and 3: Defining group differences before and after ACLR

Inferential statistics assessed the null hypothesis of no difference within and between groups for each of the primary parameters. Due to the need to include covariates in the analysis, all primary analysis were run in the univariate GLM function of SPSS using ANCOVA, reverting to the appropriate t test when covariates did not reach a statistically significant effect. Covariate effects are presented in separate tables prior to the final analysis. Independent (Question 1 and 3) and paired (Question 2) tests were used for the appropriate group characteristics. The mean differences were considered as a percentage and used to compare the effects between parameters. Effect size was calculated for all inferential analysis. For t-tests and non parametric tests, effect size r was calculated using the equations described by Field (2009) and interpreted according to Cohen's (1969) guideline, > 0.5 is a large effect, 0.3 – 0.49 medium, 0.1 to 0.29 small, and < 0.1 trivial. For ANCOVA partial Eta squared is presented.

Questions 1 and 3: Defining recovery with clinical significance criteria

Recovery was assessed using the clinical significance methods proposed by Jacobsen et al. (1984) and Jacobsen and Traux (1991). The original methods propose that recovery occurs when a parameter reaches a level that is with 2 SD below the healthy mean. This standard has been debated as too stringent for those with conditions that are unlikely to fully recover and too low for those who expect full recovery (Cisler et al., 2005; Wise, 2004). In these cases where full recovery is expected several authors have suggested a cut off of 1 SD (Kendall et al., 1999; Ogles et al., 2001; Kadzin et al., 2008) or 0.5 SD (Cisler et al., 2005) may be a better standard by which to define recovery. In a comprehensive review of meaningful change indices Norman et al. (2003) demonstrated that meaningful change was most often detected at levels of change of half a standard deviation. This level of change is also consistent with Miller's (1956) observation of the limits of human discrimination. Norman et al., (2003) also observed that meaningful change was related to the expectation of recovery, with greater change required in those subjects expecting full recovery to pre injury function. Since there is an expectation of full recovery within this group and that recovery has been defined as the subjects feeling unidentifiable from the healthy population (i.e. to consider themselves fully recovered) the 0.5 SD standard was considered more appropriate. Use of this more stringent cut off would mean that those passing it are unequivocally recovered

(Wise, 2004). This standard of full recovery would make the individual equivalent to the best performing 69.1% of the healthy population. This logic was also used to define partial recovery as a distinguishable difference from full recovery within the next half a SD, i.e. within 1 SD below the healthy mean. This standard would include 84.1% of the healthy population. Below 1 SD from the healthy mean (i.e. in the lowest 15.9% of the healthy population) subjects were considered distinguishable from full and partially recovered and therefore having failed to recover sufficiently to have achieved the expectation of ACLR and rehabilitation. Changes over time were considered clinically significant (either improved, the same or worse) on the basis of the reliable change index (RCI = 1.96xSEmean) for that outcome. Table 12 demonstrates this process when applied to the IKDC SKF using healthy data published by Anderson et al. (2006). At each age and gender point a normative comparison can be made at the mean -0.5SD level indicated in the "norm" column.

Table 12: Age and gender matched normative values for the IKDC SKF (Anderson et al., 2006).

age group (years)	**male**				**female**			
	mean	**95%CI**	**SD**	**norm**	**mean**	**95%CI**	**SD**	**norm**
18-24	95.5	94.7-96.3	8.2	91.4	93.4	92.5-94.3	9.5	88.9
25-34	94.6	93.7-95.4	9	90.1	92.5	91.6-93.5	10.9	87
35-50	93.1	92.2-94	9.9	88.2	90.7	89.6-91.8	12.3	84.5
51-65	88.4	87.2-89.6	13.7	81.5	84.7	83.2-86.3	16.2	76.6

Key: CI = confidence interval, SD = Standard deviation, norm = mean minus 0.5xSD value used to define recovery.

Question 3: Defining success

Following the recent consensus opinion developed by Lynch et al. (2015), success was defined as a functionally stable (Lysholm instability subscale) knee with a symptom free (IKDC SKF age and gender matched normative values, Andersson et al., 2006) return to preinjury participation (Tegner score).

The standards for success were defined as follows. Functional stability was defined by the Lysholm stability subscale, a report of no instability (25 points) was considered successful, a score of rare instability with strenuous activities (20 points) as partially successful and any lower score as unsuccessful. Participation was defined by recovery in comparison to retrospective pre-injury reports, with those achieving the same level or higher considered successful, those within 2 points as partially successful and those below that as failed. The 2 point cut off was selected on the basis of the calculated SEM (Letchford et al., 2015) and has also been previously used by Thomeé et al. (2008) for the same purpose. The standards for the function measure (IKDC SKF) were defined by clinical significance methods. Success is defined by achieving within 0.5SD from the mean of the age and gender matched healthy values (Andersson et al., 2006), partial success between 0.5 and 1 SD from the healthy mean and failed if > 1 SD from the healthy mean. These methods are similar to those used by Grindem et al. (2012) and Logerstedt et al. (2012) in studies assessing limb symmetry during hop for distance as predictors of outcome, although both defined groups as pass or fail on the basis of normative IKDC SKF. Both used log regression to assess predictors and ROC to assess sensitivity and specificity for different levels of LSI.

Question 4: Identifying predictors with multivariate linear regression.

The literature review identified potential predictors from the injury and pre-operative pathway characteristics and the pre and post-operative activity performance parameters. Since there was no strong evidence available, the application of stepwise methods with backward selection was justified to select predictors on the basis of statistical criteria (Field, 2009). Colinearity statistics and residual diagnostics were performed. The adjusted R squared was used to indicate how much variability in success was accounted for by each predictor variable and each of the predictor models.

When activity parameters were considered significant predictors of successful outcome, further investigation of the level of performance was required to define recommendations for clinical milestones. This was achieved using Receiver Operator Characteristic (ROC) curve method to assess the specificity and sensitivity of the parameter on a binary classification of recovery. The ROC curve method (Fawcett, 2006) was used to calculate sensitivity (true positive) and specificity (true negative) values for each level of a variable against a binary classifier. The sum of sensitivity and specificity was used to identify the level of the variable at which the fewest misclassifications on the binary classifier occur. In this instance the activity parameter (gait velocity, squat depth and hop distance) was used to predict future classification as recovered or not recovered. The level of each activity parameter with the fewest misclassifications (highest sum of specificity and sensitivity) was selected to define the binary group i.e. recovered or not recovered. The area under the curve (AUC) was used as a summary statistic; it is equivalent to the probability that the classifier will rank a positive result higher than a negative result, and is therefore equivalent to Wilcoxon rank test (Fawcett, 2006). AUC ranges from 1 (perfect classification) to 0.5 (random classification).

Results

This chapter will present the results of the data analysis using inferential statistics, clinical significance criteria and regression methods. It is split into 3 sections, the first deals with the sample and data characteristics and pilot studies; the second is the primary analysis of between group differences for questions one through three and the final section presents the identification of predictors of success for question four.

The characteristics of the healthy and injured groups are presented first, with details of the matching process and the requirement for covariate analysis. The characteristics of injury (structure parameters) and the pathway of care before and after surgery are presented. The next section is dedicated to missing data, identifying rates and patterns of missingness and the development of appropriate imputation models to create the final data set for analysis. Pilot studies are then presented; the reliability of the measurement of sagittal kinematics using Silicon Coach for the hop and squat data, a comprehensive analysis of measurement properties of a novel 2D telescopic inverted pendulum model (Letchford et al., 2014) and a comparative analysis of measurement properties for four participation PROMs (Letchford et al., 2015). The primary analysis is presented for each of the four questions in turn.

For the group comparisons in questions one to three, descriptive and inferential statistics are presented for the appropriate groups and where appropriate clinical significance criteria are applied. Parameters for structure, function and participation domains of the WHO ICF are presented first, followed by an assessment of subjects using the concept of functional coping, adapting and non-coping. Activity parameters are presented for both performance and strategy, with exploration of any interactions and identification of patterns and subgroups when appropriate. Finally, the analysis for question four is presented. Composite parameters that define success are developed and presented before the results of a regression analysis to identify predictors of success across the domains of the ICF. The activity parameters are investigated for predictive capabilities and the longitudinal data is used to identify where they may make useful contributions as clinical milestones to predict successful outcome.

Recruitment

Injured subjects were recruited from the ACLR review service at the Royal Gwent Physiotherapy department between January 2011 and March 2013. Healthy subjects were recruited from staff and students within the Health Board and Cardiff University over the same period. A total of eighty five ACL injured patients and sixty one healthy subjects gave informed consent to participate in the study. Eight ACL injured participants (3 Female, 8 Male) were subsequently removed from the study; four elected to cancel the surgery, 3 had associated surgical procedures that met exclusion criteria (2 microfractures and 1 MCL reinforcement) and 1 sustained a dislocation of the patella at 8 weeks following ACLR. From the sample of 77 subjects, just 3 were lost to follow up leaving a final sample of 74 ACLR subjects.

Group characteristics

Descriptive statistics for the demographics of the healthy and injured samples are presented in Table 13 and are represented graphically by population pyramids in Figure 10. Only height (D(135) = 0.072, P = 0.085) was normally distributed whilst both age (D(135) = 0.092, P = 0.007) and mass (D(135) = 0.082, P = 0.025) were not. There were no significant differences between the groups in height (t(133) = 1.053, P =0.294, r = 0.091) or age (U (135) = 1994.5, Z = -1.161, P = 0.124, r = 0.010). However, the healthy group were significantly lighter (U = 1283.5, Z = -4.304, P <0.001, r = 0.370), less active (U = 1154.0, Z = -5.016, P<0.001, r = 0.43.) and showed a trend to having more females (U = 1963.5, Z = -1.848, P = 0.078, r = 0.16). Whilst the distribution of these parameters between the two groups showed some mismatches, overall the matching was good. Due to the significance of the difference in mass between the groups, this parameter will be considered as a covariate throughout the analysis.

Every effort was made to consider the needs of the matching process during recruitment of the healthy group. However, the groups were recruited simultaneously and therefore keeping this process accurate was challenging. At the time of completing the analysis resources did not allow the recruitment of more healthy subjects to correct the minor differences and it was not possible to manipulate the healthy group to improve the matching. Therefore demographics were considered as possible covariates for inclusion in the analysis. The effect of these small group differences in demographics on the activity parameters were explored through correlation analysis (Table 14).

Within the healthy group hop distance is the only parameter to be correlated to any of the demographic parameters. There is a highly significant ($P<0.001$) correlation with gender ($r = 0.563$), height ($r = 0.550$) and weight ($r = 0.368$) such that taller, heavier males hop further. These demographic variables are however also all highly significantly correlated with each other ($P<0.01$); height and gender are correlated highly ($r = 0.627$) and both gender and weight ($r = 0.414$) and height and weight ($r = 0.521$) are moderately correlated, confirming what might be expected that males are generally taller and heavier. Height was therefore considered the best parameter for normalisation of hop distance to account for this interrelatedness in the analysis.

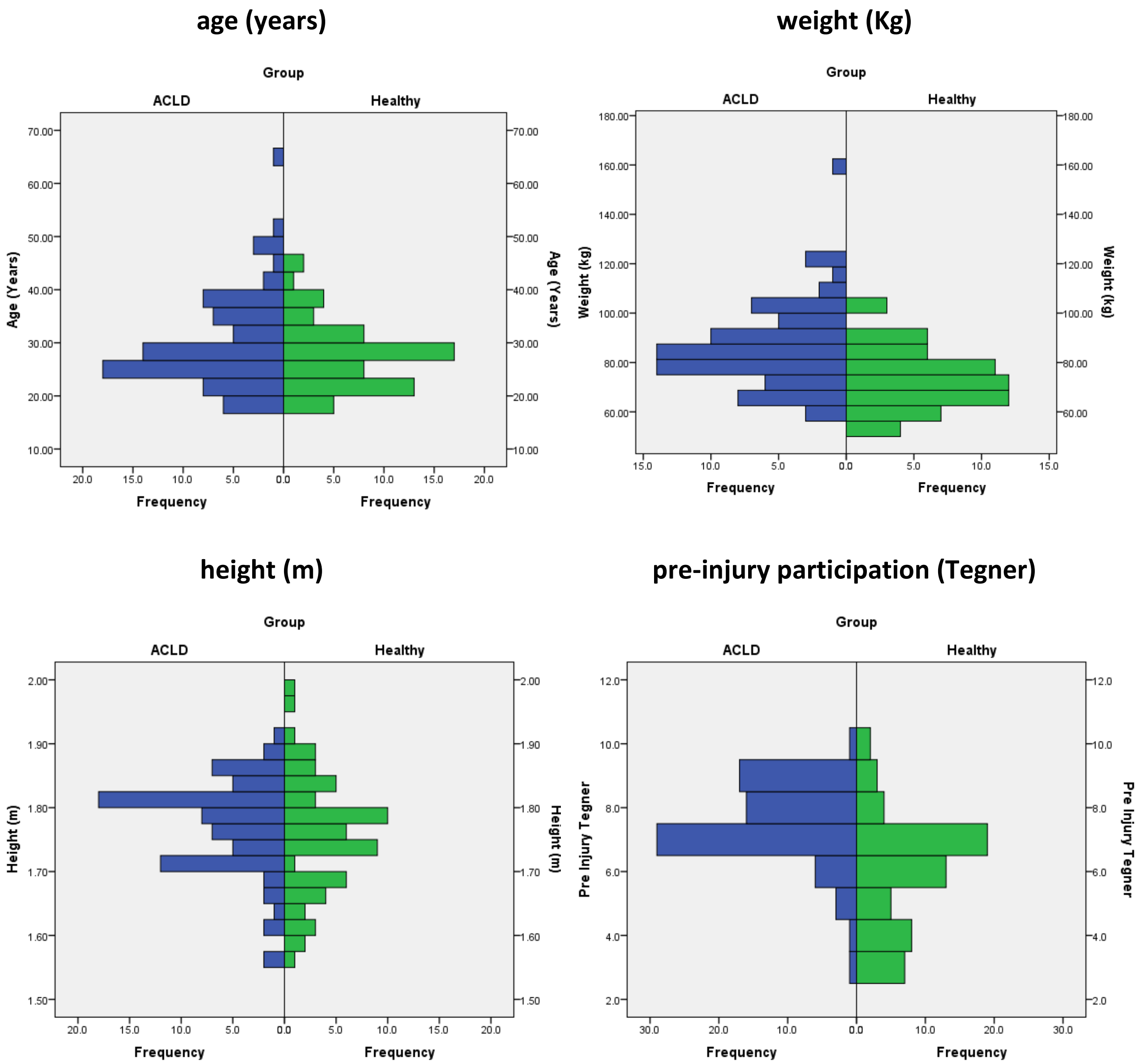
Within the ACLD group the same pattern of correlation was seen for height and gender. There was no significant correlation between hop distance and weight. This correlation was further explored for those subjects that refused to hop at the preoperative visit. The distribution of weight for the 17 subjects who refused to hop is shown in Figure 11. Those that refused ($M = 99.553$, $SE = 4.890$) the hop test are significantly ($U = 207.5$, $Z = -3.560$, $n = 74$, $P <0.001$, $r = 0.414$) heavier than those that completed ($M = 81.875$, $SE = 1.871$). Neither gender ($U = 465.0$, $Z = -0.407$, $N = 74$, $P = 0.512$, $r = 0.047$) or height ($t(72) = 1.479$, $P = 0.143$, $r = 0.172$) were different between the groups for refusal to hop. In the ACLD group weight is correlated to both squat depth and gait velocity such that heavier subjects walk slower and

Table 13: Demographics of study participants in healthy and injured cohorts. Statistically significant differences (P<0.05) occur in weight and activity level and are highlighted in greyscale. The groups have a trend to differences in age and gender.

Group	n	Gender		demographics			Participation
		male	female	Age (years)	Height (m)	Mass (Kg)	Tegner
injured	74	63 (85%)	11 (15%)	30.22 (8.84)	1.77 (0.07)	85.9 (17.29)	7 (3-10)
healthy	61	44 (72%)	17 (28%)	27.89 (6.33)	1.75 (0.09)	74.2 (11.89)	6 (3-10)

Key: n = number of subjects, gender data is presented number (percentage), demographics as mean (SD), participation median (range), n = number of subjects.

Figure 10: Population pyramids showing the distribution of demographic characteristics in the healthy and ACL injured groups.



squat less deeply, whilst there were no significant correlations in the healthy group. Again, the 6 subjects who refused to squat (M = 94.5Kg SD = 15.30) had a higher mean weight than those who completed (M = 85.18 SD = 17.33); the difference was small but statistically significant (U(73) = 119.0, Z = -1.638 r =0.192 , P = 0.047). Weight will therefore require consideration as a covariate both for activity parameters and missing data due to refusal to perform an activity.

The larger number of females in the control group was a possible concern since it is known that on average females walk more slowly (Bohannon and Andrews, 2011) and hop less far than males (Reid et al., 2007; Gustavsson et al., 2006; Itoh et al., 1998). In this sample however, there were no significant differences between the genders in gait velocity, for either the healthy (male M = 1.392 SE = 0.020, female M = 1.386 SE = 0.033; $t(59) = -0.143$ $P = 0.887$) or ACLD (male M = 1.221 SE = 0.025, female M = 1.256 SE = 0.049; $t(72) = 0.566$ $P = 0.573$) group. There were however significant differences in hop distance between the genders in both the healthy ($t(59) = 6.579$, $P < 0.001$) and ACLD ($t(55) = 4.456$, $P < 0.001$) groups. Since a high correlation has been demonstrated between gender and height it was possible to account for some of this difference by normalising hop distance to height. Participation as measured by Tegner score was weakly correlated with hop (r= .277) and squat (r=.219) in the ACLD group such that subjects with higher pre-injury activity were capable of hopping further and squatting deeper. There was no correlation with participation in the healthy group data. Whilst there was a small difference in the participation characteristics of the two groups, these lower correlations suggest that any mismatch will have a small effect that was considered acceptable.

Summary

The healthy and injured groups are not perfectly matched for weight, gender and activity level; therefore these differences needed to be accounted for by inclusion of covariates in the analysis. Weight was considered as a possible covariate for both gait velocity and squat depth and hop distance was normalised to height to account for the correlated demographics and to limit the impact of the gender inequities.

Figure 11: Population pyramid showing the distribution of weight for the ACLD subjects that refused and completed SLHD at the pre-operative assessment

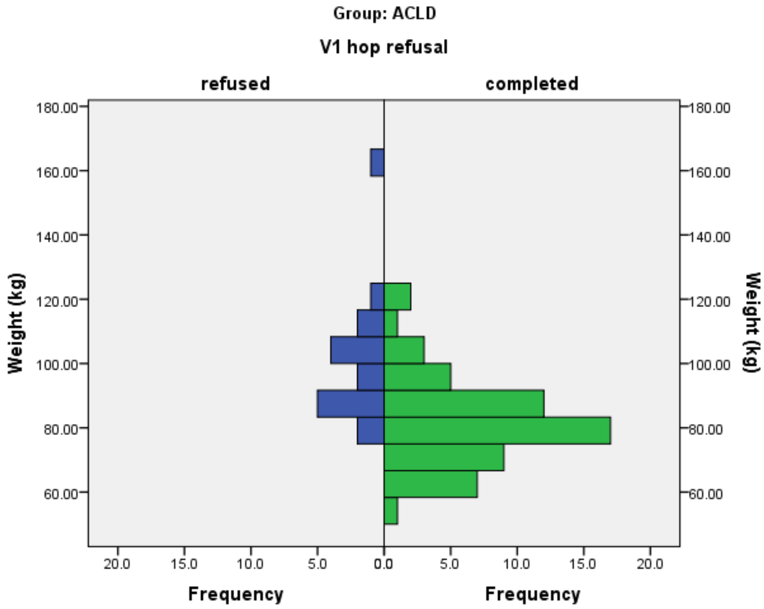


Table 14: Correlations between the primary outcomes and demographics for the ACLD and healthy group

group	parameter	statistic	age (years)	gender (M/F)	height (m)	weight (kg)	participation (Tegner)
ACLD	Gt Vel	r	.020	-.066	.018	-.258*	.067
		Sig.	.434	.287	.441	.013	.286
	Sq Rep	r	-.122	-.055	.019	-.203	.128
		Sig.	.162	.328	.439	.050	.151
	Sq depth	r	.143	-.201	-.124	.279*	-.219*
		Sig.	.124	.051	.159	.011	.037
	Hp Dis	r	-.186	.373**	.309**	-.073	.277*
		Sig.	.083	.002	.010	.294	.018
Healthy	Gt Vel	r	-.040	.019	.199	.012	-.001
		Sig.	.379	.443	.062	.465	.495
	Sq Rep	r	-.198	.210	.173	.108	-.088
		Sig.	.065	.053	.093	.205	.252
	Sq depth	r	-.034	.060	-.020	.060	.036
		Sig.	.397	.323	.441	.322	.391
	Hp Dis	r	-.210	.563**	.550**	.368**	.180
		Sig.	.052	.000	.000	.002	.082

Key: Gt Vel = gait velocity, Sq Rep = squat repetitions, Sq depth = squat depth (degrees), Hp Dis = hop distance

Injury characteristics

This section presents data for the mechanism of injury and data for frequency of tissue injuries in the knee from both MRI and examination under anaesthesia / arthroscopic assessment. Forty eight (64.9%) participants reported a non-contact mechanism to injury, the remaining 26 (35.1%) were injured in contact. MRI and MUA / Arthroscopic diagnosis of associated injuries are presented in Table 15 and 16. Two subjects did not have a pre-operative MRI scan available on the ABUHB electronic record, leaving data available for 72 of the 74 subjects.

Meniscal injury was identified in 50 knees at both MRI and arthroscopy, with agreement between MRI and arthroscopy findings in 46 knees. The remaining 24 knees had 16 (20.6%) tears identified on MRI that were not identified at arthroscopy (8 medial and 8 lateral), and 12 (16.2%) tears identified at arthroscopy that were not identified on the MRI (7 lateral and 5 medial). These differences are not entirely unexpected, arthroscopic assessment will be considered the gold standard and this data will be used in subsequent analyses.

Table 15: Number (percentage) of meniscal and chondral injuries identified on MRI and at surgery and the treatment (Rx) provided.

	Menisci				Chondral				
	n	Medial	Lateral	Both	n	Medial	Lateral	PFJ	All
MRI	50 (68%)	34 47.25%	8 (11.1%)	8 (11.1%)	11 (15%)	5 (6.9%)	2 (2.8%)	3 (4.2%)	1 (1.4%)
Surgery	50 (68%)	35 (47.3%)	10 (13.5%)	5 (6.8%)	9 (12%)	6 (8.1%)	2 (2.7%)	0	1 (1.4%)
Rx	Resected = 31 (60.8%) Repaired = 17 (33.3%) Stable not treated = 3 (5.9%)				None treated				

Key: n = number of subjects, PFJ = Patellofemoral joint, Rx = treatment

Table 16 : Number (percentage) of ligament injuries identified on MRI and the clinical grading of laxity at MUA

Ligament	MCL	LCL	ACL	PCL	PLC
Abnormal on MRI	8 (11.1%)	5 (6.9%)	72 (100%)	1 (1.4%)	1 (1.4%)
Stress test grade at MUA	0 = 74	0 = 74	I = 19 II = 44 III = 11 Pivot = 72	0 = 74	0 = 74

Key: Grading is according to the American Medical Association (grade 0 to III) described in McCluskey and Blackburn (1980). MCL = medial collateral ligament, LCL = lateral collateral ligament, ACL = anterior Cruciate ligament, PCL = posterior Cruciate ligament, PLC = posterolateral corner, Pivot = pivot shift manoeuvre.

Of the 50 tears identified at arthroscopy, 3 were deemed stable and not requiring treatment, 17 were repaired and 30 considered irreparable and therefore resected to a stable margin. Meniscal injuries were dummy coded on a three point scale; before surgery this was none, one or both. Meniscal injury was not correlated to time from surgery (r(74) =0.11, P = 0.461) and there was no significant difference (t(72)= -0.097, P = 0.894) in the time to surgery in the group with meniscal injury (M = 18.1 months, SD 15.1) and those without (M = 17.8 months, SD = 15.8) or between (t(46)= 0.232, P = 0.817) those that were repairable (M =18.1 SD = 14.5) and resected (M = 19.2, SD = 17.8).

Chondral injury was identified in 11 knees at MRI and 9 at arthroscopy. 6 were to ICRS grade 1, 1 to grade 2 and 2 to grade 3. There was agreement between MRI and arthroscopic findings in 64 cases, in the remaining 8 there were 5 MRI identified lesions that were not apparent at arthroscopy and 3 identified at arthroscopy that were not on MRI. Bone bruising was identified in 32 knees, 18 affecting the lateral compartment, 7 the medial compartment and 7 the patellofemoral compartment.

The ACL was identified as abnormal on all 72 MRIs and all 74 subjects had a positive Lachmans during examination under anaesthesia (MUA) at the time of surgery (19 grade 1, 44 grade 2 and 11 grade 3). Just 2 knees did not have a positive pivot shift. Minor abnormalities were identified in the other knee ligaments on MRI, the MCL was abnormal in 8, LCL in 5 and the PCL in 1. However at MUA all of these ligaments were identified as stable. Further exploration of the relationship between these injury characteristics, pathway parameters and knee function will be explored in the presentation of pre-operative data in response to question one.

Therefore, this group have isolated ACL injuries with only minimal damage to the other knee ligaments. All are passively unstable during Lachmans and all but two during pivot shift under anaesthesia. 68% of subjects have a meniscal injury.

The pathway of care

This section describes the pathway of care from injury to 1 year following ACLR. Data includes time to diagnosis, time to surgery, recognition of post injury or pre-operative rehabilitation and post-operatively rehabilitation attendance and discharge times.

Time to diagnosis

Diagnosis was defined by the time of MRI confirmation of an ACL injury. Time to MRI was not normally distributed (D(74) = 0361. P <0.001) due to a positive skew (6.113 SE = 0.297). One significant outlier (259 months) was replaced with the next highest plus one; 73 months and a log 10 transformation applied. The mean time to MRI was 10.3 months (SD = 16.5), over half (55%) of subjects had MRI within 3 months of injury and 71% within 6 months. There was however a significant tail with 18% having MRI over 1 year from injury.

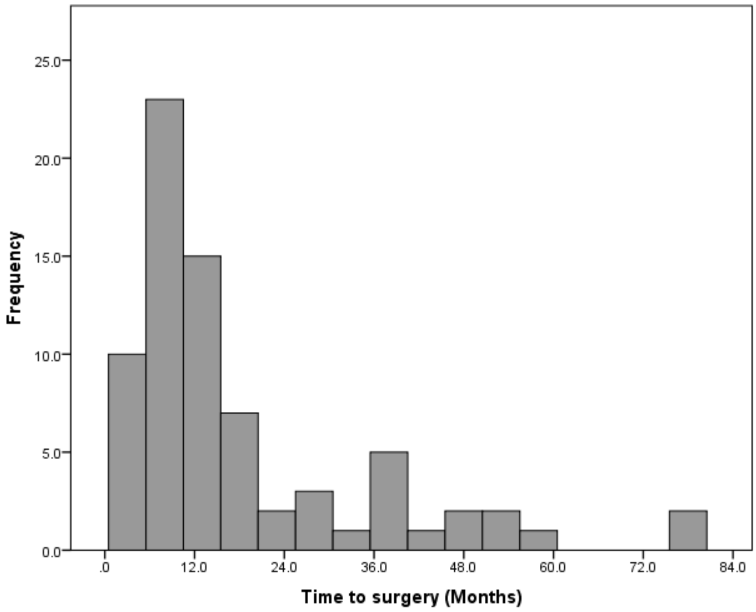
Time to surgery

The distribution of time from injury to surgery is presented in 11. Time to surgery is not normally distributed (D(74) = 0.235. P <0.001) due to a positive skew (1.859 SE = 0.279). One significant outlier (271 months; z=7.54) was replaced with the next highest plus one; 79 months and a log 10 transformation applied. The mean time to surgery is 18.5 (SD=16.82) months with a range from 3-79. The majority of participants (77%) received surgery within 24 months of injury, however there is a significant tail on the distribution between then and 60 months. The relationship between these pathway characteristics, injury parameters and knee function will be explored in the presentation of pre-operative data in response to question one.

Pre-operative intervention

Four (5.4%) participants reported using a knee brace immediately after injury and 33 (44.6%) reported attending a rehabilitation programme between injury and surgery. The content of these rehabilitation programmes was unfortunately not available within this study.

Figure 12: Distribution of time to surgery for the study sample



Post-operative rehabilitation attendance

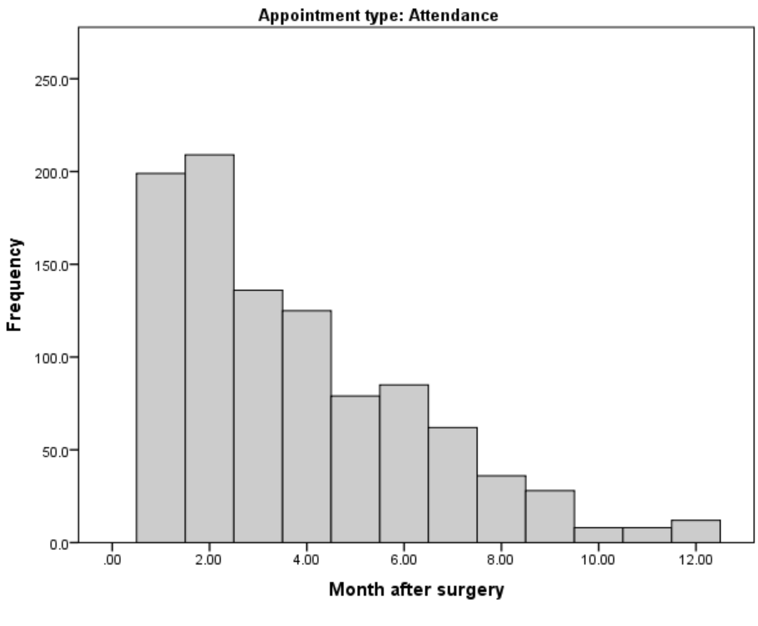
The distribution of attendance at rehabilitation is shown in Table 17 and Figure 13. Two participants were transferred out of the area for rehabilitation in the period between 3 and 6 months following surgery, leaving data for 72 subjects. Over half of the rehabilitation attendances occurred in the initial 3 months following surgery and nearly 85% by 6 months. Very little rehabilitation contact was occurring beyond 6 months from surgery despite this being the period when functional training and graduated return to sport is recommended by the rehabilitation protocol. The early rehabilitation (< 6months) period was also the period during which there was the highest number of cancelled and rescheduled rehabilitation appointments.

Table 17: Attendance at rehabilitation during the first 12 months following surgery

appointment Type		month after surgery												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
att	**freq**	199	209	136	125	79	85	62	36	28	8	8	12	987
	%	20	21	14	13	8	9	6	4	3	1	1	1	100
	cum	20	41	55	68	76	84	91	94	97	98	99	100	
CNA	**freq**	12	20	19	19	20	15	22	8	6	3	1	4	149
	%	8	13	13	13	13	10	15	5	4	2	1	3	100
	cum	8	22	34	47	60	71	85	91	95	97	97	100	
DNA	**freq**	8	16	13	13	11	12	4	2	6	1	1	1	88
	%	9	18	15	15	13	14	5	2	7	1	1	1	100
	cum	9	27	42	57	69	83	88	90	97	98	99	100	
CC	**freq**	10	11	11	8	6	6	4	2	1	1	1	1	62
	%	16	18	18	13	10	10	7	3	2	2	2	2	100
	cum	16	34	52	65	74	84	90	94	95	97	98	100	
DC	**freq**	0	1	1	7	5	6	17	5	4	8	1	17	72
	%	0	1	1	10	7	8	24	7	6	11	1	24	100
	cum	0	1	3	13	19	28	51	58	64	75	76	100	

Key: freq = Number of attendances, % = percentage of total attendances, cum = cumulative percentage, att = attendance, CNA = could not attend, DNA = did not attend, CC = clinic cancelled by hospital, DC = discharged from rehabilitation.

Figure 13: Number of attendances at rehabilitation for each month of the study period after surgery



Timing of data collection

Distribution data for the timing of data collection in days from surgery is presented in Table 18. This shows that there is only minor deviation from the target at each visit. The only overlap is at visit 2 where one subjects is seen at 82 days which is inside the distribution for visit 3.

Table 18: Timing of data collection

visit (months)	number of subjects	days from surgery			
		mean	SD	Min.	Max.
pre-operative	74	-30	40	217	1
1	58	31	5	23	43
2	59	59	6	46	82
3	63	94	9	78	120
6	63	185	16	164	264
12	54	371	15	344	424

Key: SD = standard deviation, Min = minimum, Max = maximum

Distribution of the parameters

Demographics

Height was normally distributed. Weight was not (positive skew), however replacement of one outlier with weight 160 kg, achieved a normal distribution. Age was not normally distributed (positive skew), there were 2 outliers with age > 50 which when replaced left a normally distributed data set. Time to surgery was not normally distributed (positive skew), there were 2 outliers who did not influence the distribution however log 10 transformation was effective.

PROMS

Lysholm and IKDC SKF were negatively skewed with no outliers, reverse score square root transformation resulted in a normal distribution. VAS pain was positively skewed, the square root transformation did not give a non significant K-S, however it was very close to normal with mean = 0.00, SD = 0.993, skewness = 0.195 and kurtosis -0.278, which given the aforementioned robustness of the statistical tests, was considered suitable.

Activity measures

All gait parameters were normally distributed. Both squat parameters were negatively skewed. PKF had 4 outliers (1 injured subject and 2 healthy subjects) for the non-injured leg and 5 (2 injured and 2 healthy) for the injured leg, replacement of these was effective in creating a normal distribution. The distribution of squat repetitions improved towards normal with square root correction (M = 0.00, SD = 0.992, Skewness = 0.360 and kurtosis = -0.040), whilst K-S remained significant, the histogram and descriptive statistics indicated that deviations from normality were small and were therefore considered appropriate. Hop distance was normally distributed. All TIP parameters were normally distributed except TIP length at PKF. For the injured leg, replacement of 4 outliers (2 injured and 2 healthy) left a significant K-S, however the graphs and distributions (M = 0.000, SD = 0.989, Skewness = -3.24 and Kurtosis = -0.038) indicated minimal deviation from normal and were therefore considered acceptable. For the non-injured leg replacement of 10 scores with TIP L < 90 resulted in a non significant K-S. Kinematics parameters were all normally distributed.

Missing data analysis

This section will present the frequency and patterns of missing data following the principles set out in the methods section (Statistical analysis – Missing data). The MAR/MCAR assumption is tested for each of three identified mechanisms (non-attendance, refusal to perform a task and technical error) of missing data and correlation analysis used to identify potential auxiliary variables for inclusion in the missing data models.

Missingness within the complete data set

Missingness for the primary variables is represented graphically in Figure 14. Of the 3256 data points (values), there were only 648 (19.9%) with missing data. Since these were distributed across a majority of the subjects (n = 57) the number of complete variables has a somewhat misleading appearance of a large amount of missing data. However the missingness patterns presented graphically in Figure 15 provide reassurance that the missing data is spread thinly across many subjects at very different time points and variables. The missing data patterns are random and non-monotone, giving reassurance that drop out was not a concern. The most common pattern is that of complete data. These patterns provide support for the MAR/MCAR assumption, which is further supported by a non-significant Little's MCAR test (Chi Square (1836) = 1707.203 P = 0.985).

Missing data mechanisms

Three mechanisms for missing data were identified; non-attendance at clinic, refusal to perform the activity tests and technical errors during data extraction. The distribution of these is detailed in Table 19. No attendance represents the greatest amount of missing data whilst technical error was very infrequent. Each of these will be further explored to identify possible violations of the MAR/MCAR assumption and to identify if these auxiliary factors should be included in the missing data models.

Figure 14: Pie charts demonstrating the distribution of missingness for the primary variables. Variables are IKDC SKF, Lysholm, Tegner, VAS pain, gait, squat, hop and hop TIP across the 6 visits, cases are the 74 participants and values are the total number of attendances.

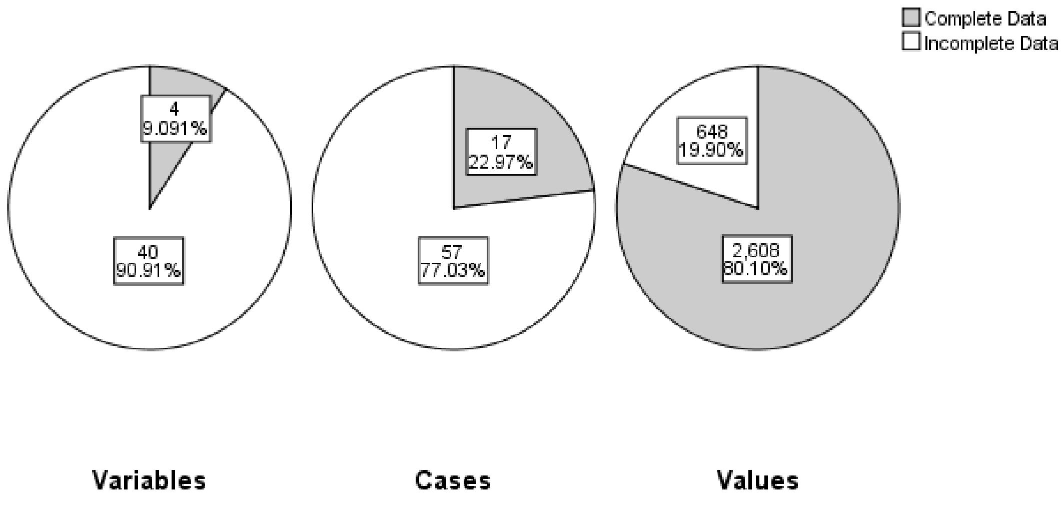
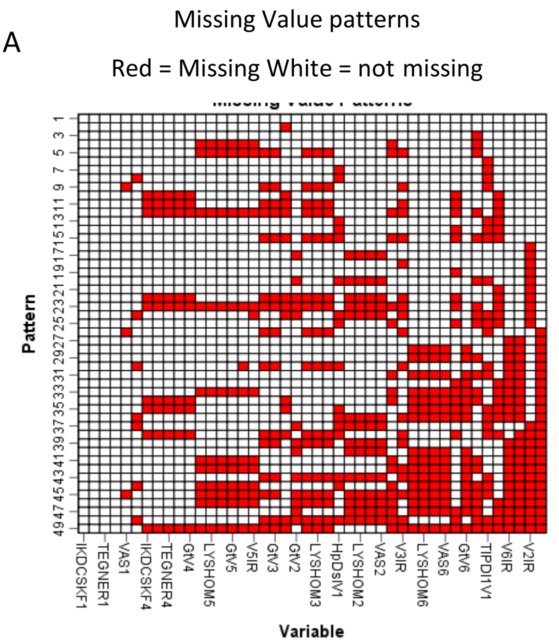
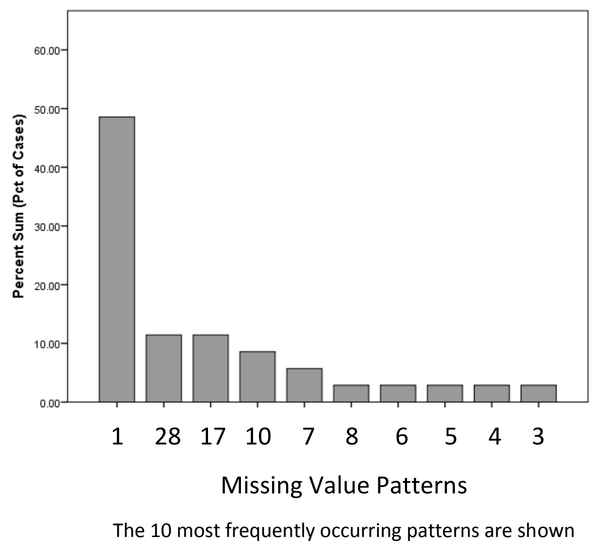


Figure 15: Missing value patterns for the primary variables

A



B



Key: A, Missing value patterns are represented on the y axis (numbered 1 to 49), the missing variables (visits) are represented on the x axis. Red shading indicates missing data, white shading complete data. The random pattern of shading represents a non monotone random pattern of missing data. **B,** The 10 most frequent missing data patterns are displayed on the x axis, the numbers correspond to the patterns on the y axis in A, with the percentage of missing data on the y axis. The most frequent pattern is that of no missing data.

Table 19: Reasons for missing data at each follow up; the number of subjects with missing data at each visit due to non-attendance, refusal to undertake an activity test or technical error in data acquisition or processing

			visit (months post op)					
			pre	**1**	**2**	**3**	**6**	**12**
missing	**non-attendance**		0	16	15	11	11	20
	refusal	**gait**	7	10	4	4	1	4
		squat	5	10	4	2	0	4
		hop	17			9	6	5
	technical error	**gait**	0	0	0	0	0	0
		squat	2	0	0	2	1	0
		hop	6			3	4	2

Missingness due to non-attendance

Missingness due to non-attendance at the review clinic is displayed in Figure 16. The pre-operative visit was complete for all subjects, however all subsequent visits had one or more non-attendances. There are 31 (42%) participants who attended all visits and 371 attendances from a total of 444 that were planned, leaving a total of 16.4% missing data. Missing data patterns are represented in Figure 17, the random pattern of shading indicates a random non-monotone pattern which again indicates no issues with drop out and supports the MCAR/MAR assumption. There are significant but low correlations between non-attendance and baseline Lysholm ($r = 0.171$), IKDC ($r = 0.231$) and pain ($r = 0.237$) supporting the MCAR/MAR assumption and indicating that these variable will be useful to the missing data models. Little's MCAR test is significant (Chi Square (67) = 92.281 $P = 0.022$) suggesting that the MCAR assumption is not supported. On balance the MAR assumption remains supported by this data.

Figure 16: Missing data analysis performed for attendance at the review clinic. Variables refer to the visits (1-6), cases to the participants and values to the total number of attendances planned.

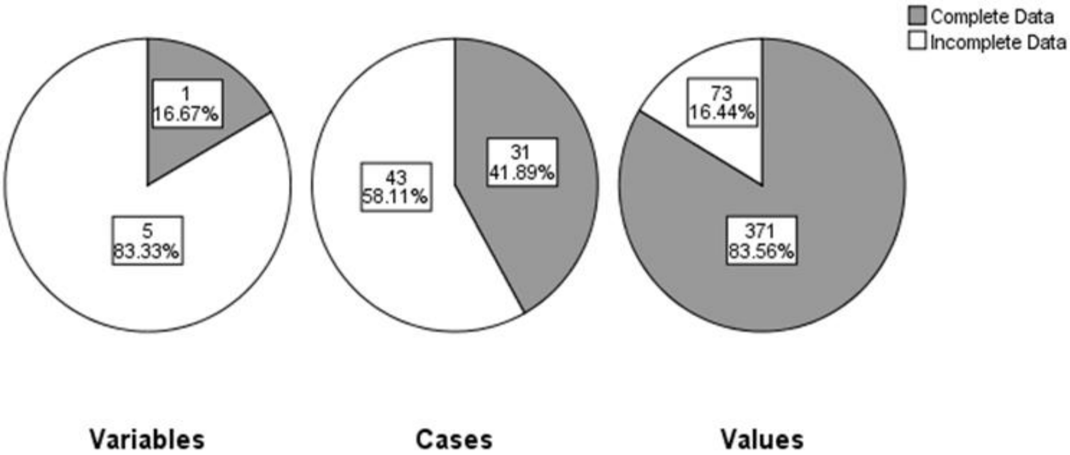
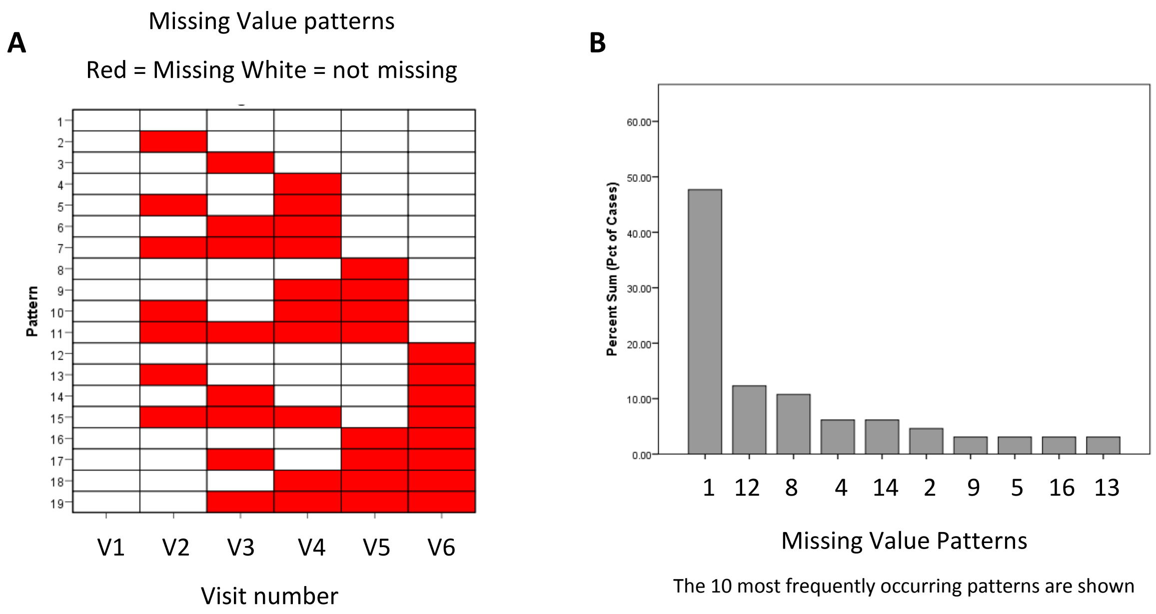


Figure 17: Missing value patterns for attendance at review clinic



Key: A, Missing data patterns are represented on the y axis (numbered 1 to 19), the missing variables (visits) are represented on the x axis. Red shading indicates missing data, white shading complete data. The random pattern of shading represents a non monotone random pattern of missing data. **B,** The 10 most frequent missing data patterns are displayed on the x axis, the numbers correspond to the patterns on the y axis in A, with the percentage of missing data on the y axis. The most common pattern is that of no missing data

Missingness due to refusal of activity tests

Frequency of refusal to perform the activity tests was presented in Table 19. The functional tests have a hierarchy of missingness that fits the hypothesised hierarchy of complexity, the gait data is complete, squat data is missing on 25 (5%) occasions and hop data on 37 (12%)., Subjects refused to perform a test due to a perceived inability to complete them safely. Those that refused squat also refused hop, however some subjects did perform squat but not hop. There are significant and low correlations between refusal on the activity tests and other outcomes at baseline (Table 20) which provides support for refusal being related to baseline characteristics and therefore supports the MAR assumption. These variables will therefore be important contributors to the missing data models.

Table 20: Correlation between refusal to perform activity and baseline parameters.

baseline parameter	refusal	
	squat	hop
Lysholm	0.348	0.395
IKDC SKF	0.269	0.411
VAS Pain	0.210	0.288
gait velocity	0.387	0.412

Key: Correlation coefficient r, all are significant at P<0.001. VAS = visual analogue scale; IKDC SKF = International Knee Documentation Committee Subjective Knee Form.

Technical error

PROMs data is missing at just 2 occasions; one subject refused to complete them at V3 and the form was lost for one subject at V2. There is however PROMS data for 1 participant at V6 when they did not attend as the participant agreed to send them in through the post. There were some technical issues with the squat (5 data points) where the video clips were available for the injured limb only, an error in saving the data on the camera seems the only viable explanation. For hop there were 14 data points where TIP parameters could not be extracted due to the head not being visible on the video at IC. The small number of cases involved with technical error relative to the other missing data mechanisms was not considered important and was therefore not further analysed.

Healthy group missing data

Gait data is complete for all 61 subjects, there was a technical fault during the squat analysis resulting in loss of squat data for one subject. Hop distance is available for all 61 subjects, however similarly to the injured subjects, 12 healthy subjects did not have the head sufficiently visible for the TIP data extraction.

The missing data rates were sufficiently high (<20%) to require the application of a missing data model. There was sufficient evidence that the missingness is correlated to the data at baseline to support the MAR assumption. Imputation methods therefore were appropriate. Non-attendance and refusal were related to baseline characteristics and these were therefore entered into the missing data models. However, further examination was now required to identify differences in the baseline characteristics and recovery of those subjects with missing data at the final follow up and correlations between primary outcomes and missingness, in order to inform the final missing data models

Identifying variables for the imputation models

Firstly, the group was split by those attending and failing to attend for final follow up. Figure 18 shows the primary variables at each visit for these two groups and shows a clear trend of recovery that is similar in those with and without missing data at final follow up. It is therefore reasonable to suggest that similar trajectories are expected regardless of missingness at final follow up. There were however significant group differences at baseline in the Lysholm ($t(72) = 2.302$, $P = .0024$), IKDC SKF ($t(72) = 2.118$, $P = 0.038$) and VAS pain ($t(69) = 2.148$, $P = 0.035$), such that those that were more symptomatic pre-operatively were less likely to attend final follow up, these variables will therefore be important to the missing data model. The group was then split by those that attended all follow ups and those that failed to attend at one or more. Group differences at baseline were significant only for the IKDC SKF ($t(72) = 3.114$, $P = 0.003$, $r=0.34$).

Correlations between variables were explored in order to inform which variables were entered into the models. Table 21 demonstrates where there were significant correlations and where these met the $r>0.4$ level proposed in the methods. All variables reaching this level were entered into the model, however due to their low number, others with lower but significant correlations were included to try and improve the model output. The variables selected for the final models are presented in Table 22.

Figure 18: Distribution of primary outcomes over time according to missingness at final follow up. Subjects with complete data at final follow up are in grey, those with missing data are in white. The trend is similar between groups.

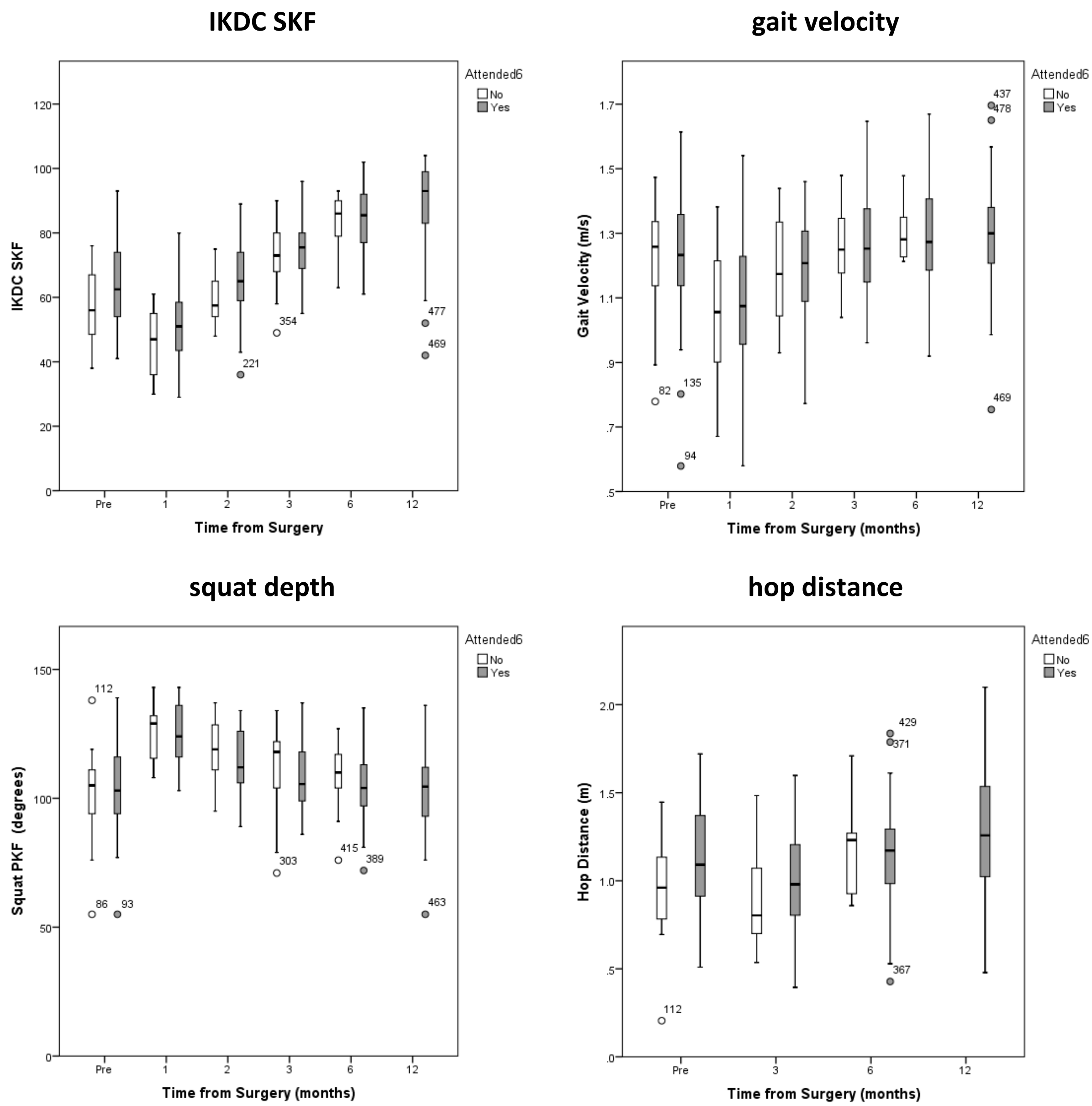


Table 21: Correlations between variables that were considered for inclusion in the missing data model.

	IKDC SKF	Lysholm	VAS Pain	Tegner	gait vel	squat reps	squat depth	squat refuse	hop distance	hop refuse
IKDC SKF	1	.735 **	-.662 **	.688 **	.450 **	.328 **	-.379 **	.269 **	.371 **	.411 **
Lysholm	.735 **	1	-.632 **	.466 **	.397 **	.266 **	-.218 **	.348 **	.233 **	.395 **
VAS Pain	-.662 **	-.632 **	1	-.313 **	-.386 **	-.203 **	.190 **	-.210 **	-.193 **	-.208 **
Tegner	.688 **	.466 **	-.313 **	1	.301 **	.203 **	-.327 **	.199 **	.384 **	.277 **
gait velocity	.450 **	.397 **	-.386 **	.301 **	1	.278 **	-.363 **	.390 **	.139 *	.411 **
squat reps	.328 **	.266 **	-.203 **	.203 **	.278 **	1	-.260 **		.144 *	.215 **
squat depth	-.379 **	-.218 **	.190 **	-.327 **	-.363 **	-.260 **	1		-.608 **	-.240 **
squat refuse	.269 **	.348 **	-.210 **	.199 **	.390 **			1	-.002	.454 **
hop distance	.371 **	.233 **	-.193 **	.384 **	.139 *	.144 *	-.608 **	-.002	1	
hop refuse	.411 **	.395 **	-.208 **	.277 **	.411 **	.215 **	-.240 **	.454 **		1

Key : correlation coefficient r, * Significant correlation at P<0.05, **significant correlation at P<0.01

Table 22: Variables included in the imputation models for the primary variables.

Parameter	gait	squat	hop	PROMS
weight	Y	Y	Y	
Tegner			Y	
IKDC SKF	Y	Y	Y	
Lysholm	Y	Y		
VAS	Y	Y	Y	
gait velocity		Y	Y	Y
cadence				
step length				
squat depth	Y		Y	Y
squat repetitions	Y		Y	Y
hop distance		Y		Y
TIP parameters				
kinematics				

Key: Y = included in model, shaded are primary variables also included in the imputation model. Blank are not included. IKDC SKF = International Knee Documentation Committee Subjective Knee Form; VAS = Visual analogue scale; TIP = telescopic inverted pendulum.

Pilot Studies

The results of three pilot studies are presented. Two studies have been published (Letchford et al., 2012 and 2014), a brief summary of results will therefore be given here.

Pilot 1: Assessing participation in the ACL injured population: Selecting a patient reported outcome measure on the basis of measurement properties.

Table 23 provides a summary of how the four PROMs performed against the a priori defined measurement property criteria derived from the COSMIN guideline. The Tegner and IKDC reached the standard on the same number of criteria. However the weaknesses identified for the Tegner were more simply accounted for when interpreting the score clinical practice and for this reason it was the preferred scale. In summary, data from the Tegner score performed consistently well in respect of measurement properties and was preferred over the other PROMs. The important measurement properties were excellent test retest reliability (ICC 0.92), low measurement error (SEM = 0.63), smallest detectable change of 1 point for group analysis and 2 points for changes for individuals and a minimally important change of 1 point for both improvement and deterioration.

Pilot 2: Reliability of kinematic measurement of knee flexion angles during hop landing using Silicon Coach

Test retest reliability and measurement error statistics are presented in Table 24 with Bland Altman plots for agreement in Figure 19 and 20. Overall, these indicate that the method has excellent reliability with high levels of retest agreement (ICC > 0.9), low mean difference and measurement error of less than 3 degrees. The use of Silicon Coach to extract kinematic measures from digital video using a marker less system is therefore supported as a reliable method.

Table 23: Performance of the four participation PROMS against the COSMIN defined measurement property criteria, Tegner and IKDC meet the most criteria.

measurement property	criteria	Tegner	CSAS	Marx	IKDC
reliability	ICC (Grp) > 0.8	Y	Y	Y	Y
	ICC (Ind) > 0.9	Y		Y	
measurement error	SEM < 1 unit	Y			Y
	SDC (Ind) < 1 unit				Y
	SDC (Grp) < 1 unit	Y	Y		Y
content	Item development			Y	
content	Broad	Y	Y		Y
convergent	Hypothesis 1	Y	Y	Y	Y
divergent	Hypothesis 2-4	Y	Y	Y	Y
known groups validity	Hypothesis 5	Y	Y	Y	Y
	ES > 0.5	Y			Y
responsiveness	Hypothesis 6	Y			Y
floor / ceiling effects	< 15%	Y			
MIC	MIC > SDC				Y
TOTAL		**11**	**6**	**6**	**11**

Key: The performance of each PROM against the a priori criteria is presented. Y indicates that the required standard is achieved; greyscale indicates where the standard is not met. The Tegner and IKDC meet 11 of the 14 criteria, the CSAS and Marx do not perform well against the criteria in this sample. Abbreviations: ICC = Intraclass Correlation Coefficient, SEM = Standard Error of Measurement, SDC = Smallest Detectable Change, H = Healthy (Pre-injury), 12 = 12 months post-operatively, 6 = 6 months post-operatively, D = ACL deficient (Pre-surgery), ES = Effect Size, Sens = Sensitivity on the Receiver Operator Characteristic Curve, MIC = Minimally Important Change, SDC = Smallest Detectable Change.

Table 24: Test retest reliability measurements of knee flexion (degrees) in Silicon Coach

rater	ICC con (95% CI))	SEM	MD (95%LOA)
1	0.929 (0.896 to 0.951)	2.78	1.86 (-6.2 to 9.92)
2	0.920 (0.881 to 0.946)	2.91	-0.87 (-9.85 to 11.59)

Key: ICC con = intraclass correlation coefficient consistency, CI = confidence interval, SEM = Standard error of measurement, MD = mean difference, LOA = Limits of agreement. The method is highly reliable with small amounts of measurement error.

Figure 19: Bland and Altman Plots for test retest agreement of rater 2 for sagittal plane knee flexion angles (degrees)

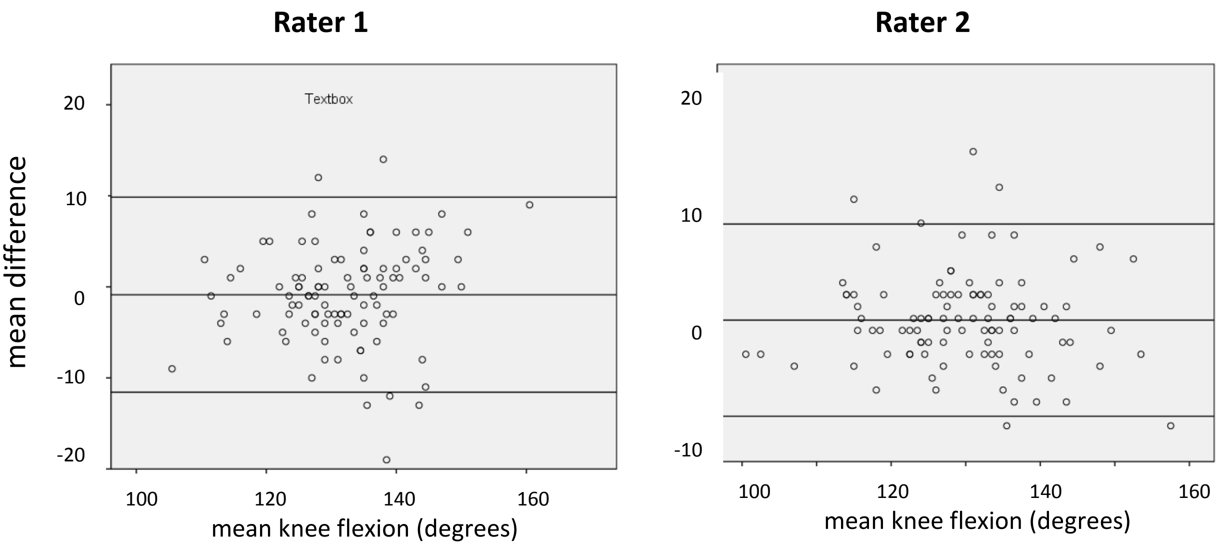
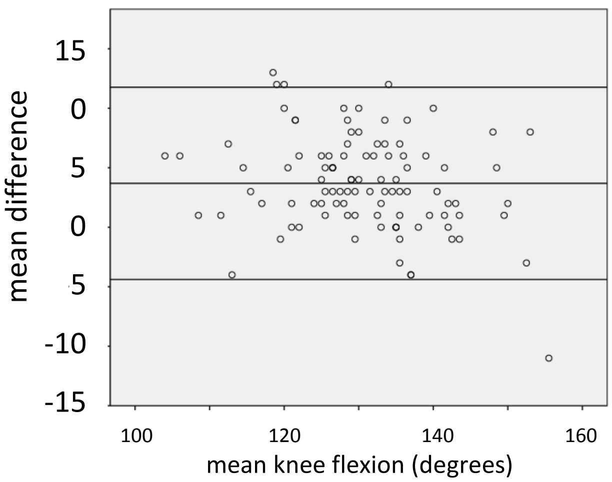


Figure 20: Bland and Altman Plots for interrater agreement of raters one and two for sagittal plane knee flexion angle (degrees)

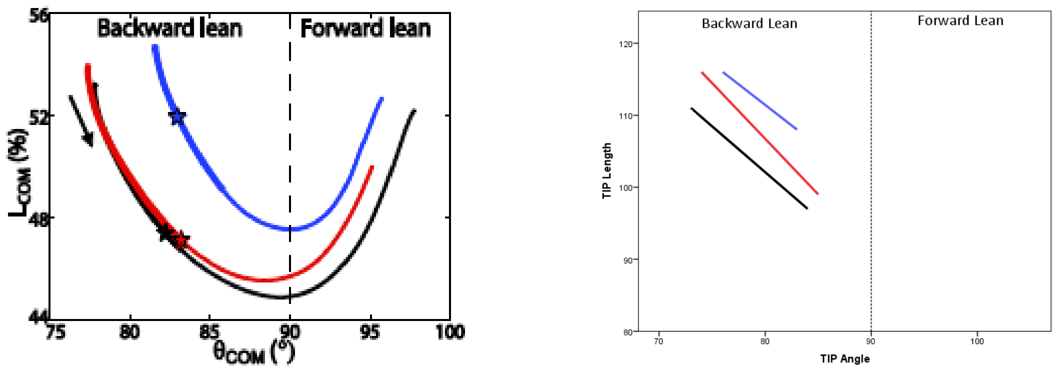


Pilot 3: 2D TIP: A novel clinical approach for assessing hop landing strategy.

The results showed that individual landmarks could be located with excellent inter rater (ICC = 0.81 – 1.00) and intra rater (0.85 – 1.00) reliability and low measurement error. The same excellent levels of reliability were observed in the calculated model centres and the parameters derived for the TIP models. The COG model was most reliable (ICC>0.96) with lowest measurement error (<9mm). Kinematic parameters also showed excellent reliability (ICC>0.96) and low measurement error (knee flexion SEM=3.05 degrees). The validity hypotheses were supported with the COG model proving to be preferable to the hip and pelvis models. The longitudinal data showed appropriate responsiveness with changes over time in accordance with a priori hypothesis for direction and magnitude. The 2D TIP tool demonstrated appropriate reliability, validity and responsiveness in this cohort. The data has further been compared to that of the 3D motion analysis system (Roos et al., 2013) in Figure 21. This demonstrates that the 2 systems identify very similar characteristics of the landing phase with the slopes between IC and PKF being very similar. There were differences in scaling due to the units of measurement and differences in the group comparison most likely due to the earlier phase following reconstruction of the current cohort.

Figure 21: Comparison of the outputs of the 3D and 2D TIP analysis of hop for distance landing strategy; Healthy subjects (Black), ACLD (Blue) and ACLR (Red), the trajectory from initial contact to peak knee flexion is similar.

3D motion analysis **2D motion analysis**



Key: TIP angle (x axis) is plotted against TIP length (y axis), the 3D system provides continuous data, the 2D system 2 points of data at initial contact and peak knee flexion.

The Main Analysis

The results will be presented for each of the research questions in turn. The domains of the ICF are used as a template for presentation. Functional stability and participation parameters are presented first in order to make an assessment of functional coping, the knee function parameters then follow. Finally, activity parameters are presented with performance considered prior to strategy. Descriptive and inferential statistics are provided for all three questions and clinical significance criteria are applied using healthy comparison in questions 1 and 3.

Question One

Question: Do differences in functional performance and knee stability exist between patients waiting for ACL reconstruction and normal values?

Functional stability

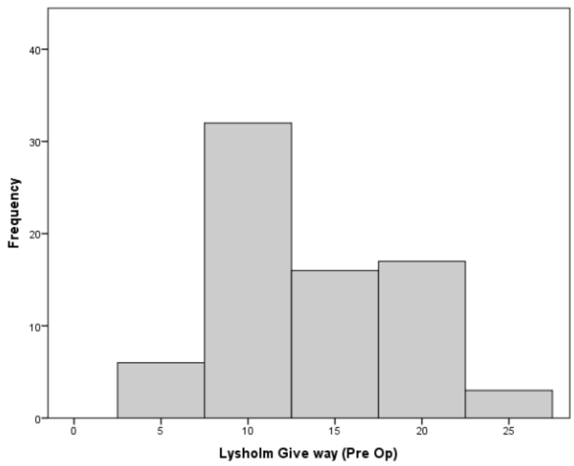
The distribution of severity of functional knee instability on the Lysholm instability subscale for ACLD subjects prior to surgery is presented in Table 25 and Figure 22. Whilst none of the subjects reported the highest level of instability “at every step”, 73% of subjects reported knee instability at the “frequently during exertion” or higher level of the scale, and a further 23 % that experienced instability “rarely with severe exertion”. This indicates that episodes of instability were common in this group and that almost all subjects were non-copers. There were three subjects who did not report functional knee instability, who may therefore be potential copers. However all three had a reduced participation score of either 4 or 5 points on the Tegner scale indicating that they are functional adaptors.

Table 25: Distribution of data from the Lysholm instability subscale for the ACLD subjects

Lysholm instability subscale		ACLD n	ACLD %
0	At every step	0	0
5	Often in ADL	6	8
10	Occasionally during ADL	32	43
15	Frequently during exertion	16	22
20	Rarely during severe exertion	17	23
25	Never gives way	3	4

Key: ADL= activities of daily living, n = number of subjects

Figure 22: Frequency distribution of the Lysholm instability subscale for the ACLD subjects



Participation

Distribution and between group differences for the Tegner score are presented in Table 26. Participation is significantly reduced in the ACL group when compared to both the healthy group and the retrospective pre-injury score. There are only 6 subjects who have not reduced participation for the retrospective pre-injury level and a further 4 who have changed by less than the 2 points minimally important difference (MID). This means that 10 patients are potential copers; however all ten report instability and therefore they are classified as non-copers. The group can therefore be divided into 71 non-copers, 3 adaptors and no copers.

Table 26: Differences in participation (Tegner score) between the ACLD and Healthy group; there were significant reductions in participation in comparison to both healthy and retrospective pre-injury levels.

parameter	group	median	IQR	paired differences			
				statistic	df	sig.	ES
Tegner (0-10)	ACLD	3	2	Z = -7.248	148	<.001	.60
	H	6	2.5				
Tegner (0-10)	ACLD	3	2	Z = -7.210	74	<.001	.84
	Pre-Injury	7	1.25				

Key: ACLD = Anterior Cruciate Deficient Subjects, H = Healthy Subjects, Pre-Injury = ACLD subjects retrospective report of pre-injury participation, IQR = interquartile range, df = degrees of freedom, ES = effect size.

Knee Function

Descriptive and inferential statistics for self-reported Knee Function, measured on the IKDC SKF, are presented in Table 27. The healthy comparator values are those of the age and gender matched normative values from Anderson et al. (2006) for this sample. On average, the ACLD subjects had a significantly lower knee function score than the healthy aged matched values; the mean difference was 33 which is a large effect (ES = 0.91). The mean difference represents a functional deficit of 33% in knee function from healthy values. The mean Lysholm knee score was 62 (SD = 8), indicating poor knee function.

The distribution of pain scores (VAS) is presented in Figure 23. The mean score was 28 (SD = 21.4, range 0-75). Using the criteria of Collins et al. (1997), 49 subjects described mild (<30mm), 14 moderate and 11 subjects severe pain (>54mm). Pain is therefore considered a common and significant symptom in this group of ACLD subjects.

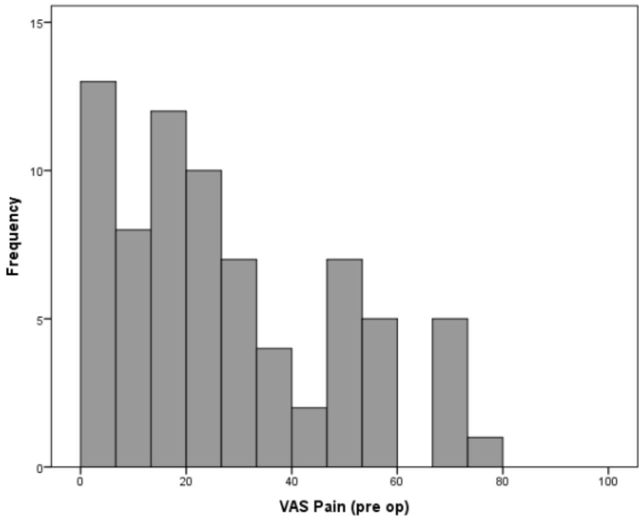
Therefore, the group had large (ES = .91) and significant (P<0.05) deficits in self-reported knee function and were experiencing moderate (mean = 28mm) intensity of knee pain prior to surgery. How these variables relate to the previously presented injury and pathway variables is of interest and is explored next.

Table 27: Differences in Knee Function (IKDC SKF) between the ACLD group and published normative values; there were significant reductions in knee function in the ACLD group.

parameter	group	mean	SE	t	paired differences					
					sig.	ES	mean	SE	95% CI	
									lower	upper
IKDC SKF (%)	Norm	89	.3	-27.872	<0.001	.91	33	1.4	30	35
	ACLD	57	1.4							

Key: Norm = mean values for an age matched normative sample, as reported by Anderson et al. (2006). ACLD = Anterior Cruciate Deficient Subjects, SE = Standard error of mean, ES = effect size, CI = confidence Interval.

Figure 23: number of subjects (frequency) reporting pain at each level of the VAS (x axis) for the ACLD group.



Relationship between function, structure (injury characteristics) and pathway characteristics.

The relationship between pre-operative function and the injury and pathway characteristics is explored with correlation (Table 28) and between group differences. Meniscal injury was significantly correlated ($P<0.05$) with the Lysholm score, such that those with meniscal injuries reported lower knee function, however the strength of the correlation was low ($r = 0.298$). There was however a significant difference in Lysholm score ($t(72) = 2.591$, $P = 0.011$; mean difference = 11, SE = 4, 95% CI = 3 to 20) between those with (M = 59, SD = 17) and those without (M = 70, SD = 17) meniscal injuries, such that those without meniscal injury had higher reported function. This was not the case for the IKDC SKF where the correlation was small and not significant and there were no significant differences (t(720 = 1.463, P = 0.148, Mean Difference = 4, 95% CI = -2 to 10) between those with (M = 60 SD = 13) and without (M = 55, SD = 12) meniscal injury. There was no correlation between bone bruise and pre-operative function. There was no significant correlation between time to surgery and meniscal injury (r=0.011, P>0.05) at arthroscopy. Frequency distribution data for meniscal injury rates when the group were split at the various intervals suggested for acquired meniscal injury (< 6 months and < 12 months) are presented in Table 29. There was again no significant correlation (r = 0.057, P = 0.632) and no significant difference in frequency of meniscal tears (Chi square = 0.263, P = 0.877) when categorised in this way.

Table 28: Correlation between structure, pathway and pre-operative function parameters in the ACLD group; significant correlations are highlighted in greyscale.

	structure		pathway		function			
	meniscal tear	**bone bruise**	**rehab**	**time to surgery**	**knee stability**	**pain VAS**	**Lysholm**	**IKDC SKF**
meniscal tear	1	-.167	-.191	.011	-.162	.094	-.298*	-.17
bone bruise	-.167	1	-.013	-.206	-.072	.044	.073	-.003
rehabilitation	-.191	-.013	1	-.002	0.017	.089	-.033	-.036
time to surgery	.011	-.206	-.002	1	.154	-.08	.078	.100
knee stability	-.162	-.072	-.017	.154	1	-.324**	.704**	.473**
pain VAS	.094	.044	.089	-.08	-.324**	1	-.571**	-.527**
Lysholm	-.298*	.073	-.033	.078	.704**	-.571**	1	.678**
IKDC SKF	-.17	-.003	-.036	0.1	.473**	-.527**	.678**	1

Key: Correlation co-efficient = r, * = Significant at P<0.05, ** = Significant at P<0.001, VAS = visual analogue scale, IKDC SKF = international knee documentation committee subjective knee form.

Table 29: Frequency distribution of meniscal injuries identified at surgery at 6 month time intervals from injury; there were no significant differences in meniscal injury rate when classified in this way.

time to surgery (months)	meniscal injury	frequency	%
<6	No	5	36
	Yes	9	64
6-12	No	9	35
	Yes	17	65
>12	No	10	30
	Yes	24	70

Activity

Prior to presenting the between group differences for the activity parameters, several parameters required investigation in order to inform which is most appropriate for use. Firstly the squat data required examination to decide if repetitions are a potentially useful parameter to include in the analysis. There was then the consideration of which repetition is used for defining the squat depth parameter. Finally, consideration was given to the selection of an appropriate comparator limb from the healthy group for the group comparisons. Healthy subjects were expected to have symmetrical performance and therefore it was considered appropriate to use the dominant leg only as a comparator. This hypothesis was tested with the data from this sample.

Selecting squat parameters

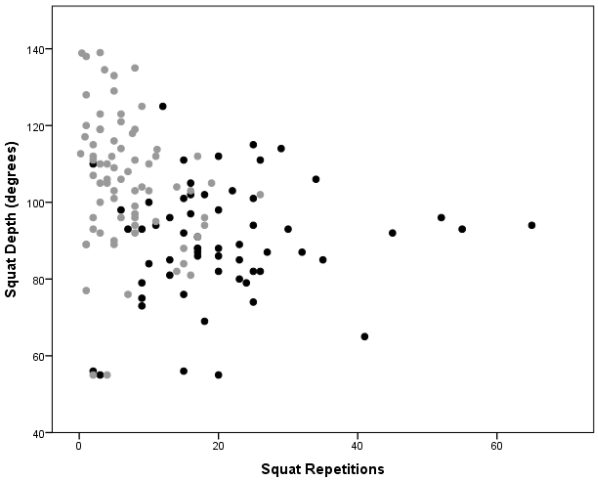
Correlations between squat depth and Reps are presented in Table 30 and graphically in scatter plot Figure 24. There was no significant correlation between squat depth and squat repetitions in any of the groups. This confirms that the parameters are measuring different aspects of squat performance and should therefore both be included in the analysis for this activity.

Table 30: Correlations between squat repetitions and squat depth parameters in the Healthy and ACLD groups; no significant correlation was identified.

group	correlation	
	r	sig.
Healthy	.116	.377
ACLD	-.222	.057

Key: ACLD = Anterior Cruciate Ligament Deficient subjects

Figure 24: Scatter plot showing lack of correlation between squat repetitions and squat depth for the ACLD (black dots) and Healthy (Grey dots) subjects.



Key: 180 degrees represents a fully straight knee, therefore greater flexion is indicated by a smaller knee angle.

Descriptive statistics for squat repetitions performed on the injured leg by the ACLD and ACLR subjects at each visit and on the dominant leg of the healthy group are presented in Table 31 and graphically for the ACLD and Healthy groups in Figure 25. Squat repetitions seemed to be an indicator of recovery with the mean showing a pre-operative deficit and gradual post-operative recovery in a pattern similar to that hypothesised for both gait velocity and hop distance. There was however a large number of participants that did not reach 5 repetitions in the pre-operative and early post-operative time period (Table 29), so a decision on which squat repetition to use for the squat depth parameter (peak knee flexion) was required. As previously explained in the methods section, squat depth parameters were extracted for the first, fifth and last repetition of the single leg squat test. Correlations and between group differences were used to inform the selection of which repetition was used.

Table 31 shows the descriptive statistics for squat depth at each level of the squat repetition. Squat depth was normally distributed for the fifth repetition (D(99) = 0.67, P = 0.200) but not normally distributed for both the first (D (127) = 0.92 P = 0.010) or last repetition (D (127) = 0.094 P = 0.007). Peak knee flexion was significantly and strongly (r>0.6, P<0.001) correlated across the three time points in all three groups (see Table 32). There was a statistically significant difference overall (Chi square (2,99) = 10.675, P = 0.005).However, there were no significant differences between the first and fifth repetition (Z(127_= -1.255 P = 0.105 r = 0.111) and a significant (Z(99) = -3.215, P = 0.001 and -3.257 P = 0.001) but small (r = 0.323 and 0.327) difference between both and the last. The high correlation and lack of significant difference between first and fifth repetition suggests that either could be used as the test for PKF. Since the first repetition had the least number of missing data the first repetition was selected.

Table 31: Descriptive statistics for the number of squat repetitions performed during the single leg squat test for the healthy, ACLD and ACLR subjects across the longitudinal data; there is a pattern of recovery over time in the post-operative data.

group	n	minimum	maximum	mean	std. deviation	N <5 reps
Healthy	60	2.0	65.0	20.650	12.253	3 (5%)
V1	67	1.0	26.0	7.179	5.494	25 (37.3%)
V2	48	1.0	19.0	5.083	4.073	26 (54.2%)
V3	55	1.0	26.0	8.691	6.310	16 (29.1%)
V4	59	1.0	30.0	11.627	7.467	10 (16.9%)
V5	62	1.0	35.0	10.726	8.328	17 (27.4%)
V6	50	1.0	33.0	13.180	9.151	8 (16%)

Key: V1 = Pre-operative ACLD subjects, V2 to 6 are the post-operative attendances at 1 (V2), 2(V3), 3 (V4), 6 (V5) and 12 (V6) months following ACLR. N<5 Reps = number of subjects performing more than 5 squat repetitions.

Table 32: Correlation coefficients for squat depth (peak knee flexion) at the first, fifth and last Squat Repetition during the single leg squat test in the Healthy and ACLD group; there were strong and significant correlations which are highlighted in greyscale.

Subjects	Repetition	Repetition		
		1	**5**	**Last**
Healthy	**1**	1	.789**	.677**
	5	.789**	1	.696**
	Last	.677**	.696**	1
ACLD	**1**	1	.867**	.926**
	5	.867**	1	.890**
	Last	.926**	.890**	1

Key: Correlation coefficient = r, ** = Significant at P<0.001

Figure 25: Cumulative frequency distribution graphs demonstrating the number of subjects performing squat repetitions (x axis) for the ACLD and healthy groups on both legs. The Mean (black line) and SD (dotted line) are displayed.

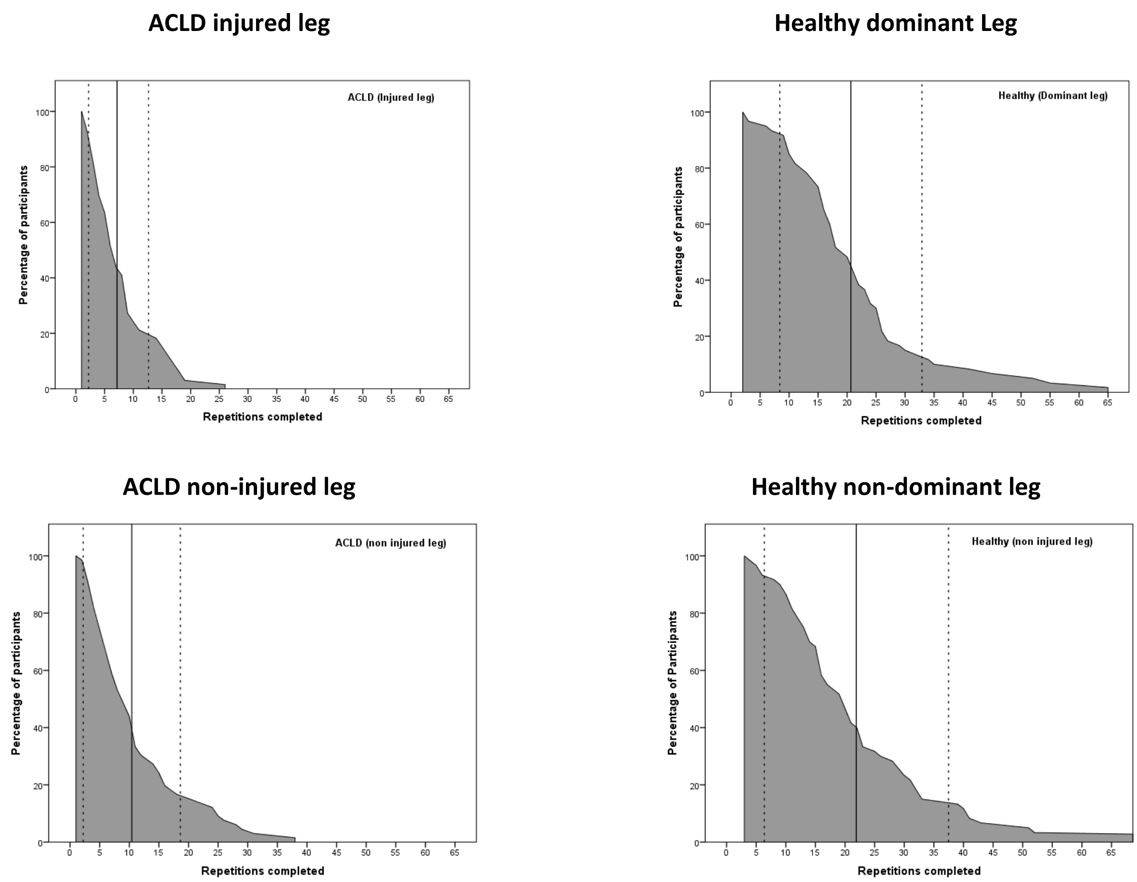


Table 33: Descriptive statistics for squat depth (peak knee flexion) at each level of squat repetition for the injured limb of the ACLD subjects.

Squat repetition	n	median	min	max	percentiles		
					25	50	75
1	127	96	29	139	87	96	110
5	99	96	63	133	87	96	108
last	127	101	24	147	89	101	112

Key: n = number of subjects, min = minimum, max = maximum

Selecting the comparator limb from the healthy group

The healthy subjects were expected to have symmetrical performance in both Hop and Squat tests with no significant difference between limbs which would therefore justify use of the dominant limb as a comparator throughout the analysis. This hypothesis was tested and the results presented below.

Between limb differences in squat.

Descriptive and inferential statistics are displayed in Tables 34 and 35. Weight was not a significant covariate for squat repetitions; however it was for squat depth and is therefore included in the analysis as a covariate. On average, there were no significant differences in squat repetitions (P=.408) or depth (P=.277), with quite large P values, between limbs in the healthy group. The dominant leg of the healthy group is therefore suitable for use as a comparator for all between group analyses.

Table 34: Exploration of subject's weight as a covariate for between limb comparisons of squat repetitions and squat depth parameters in the healthy subjects; weight was a significant covariate for squat depth.

squat parameter	leg	mean	SD	statistic	sig.	ES
repetitions	dom	21	12	F = 2.522	.115	.02
	non	22	16			
depth	dom	90	15	F = 5.363	.022	.04
	non	92	10			

Key: repetitions (number), depth = peak knee flexion (°), dom = dominant leg, non = non dominant leg, SD = Standard deviation, ES = effect size.

Table 35: Differences between limbs for squat repetitions and squat depth (peak knee flexion) in healthy subjects; there were no significant differences.

				paired differences					
parameter	leg	mean	SE	statistic	sig.	ES	mean diff	95% CI lower	95% CI upper
repetitions	dom	21	1.6	t = -0.833	.408	.11	-1	-4	1
	non	22	2.0						
depth	dom	90	1.6	F = 1.191	.277	.01	2	-7	2
	non	92	1.6						

Key: repetitions (number), depth = peak knee flexion (°),dom = dominant leg, non = non-dominant leg, SE = standard error of the mean, ES = effect size, mean diff = mean difference, CI = Confidence interval.

Between limb differences in hop distance.

Descriptive and inferential statistics are displayed in Table 36. There were on average no significant differences in hop distance (P.611) between the limbs of the healthy group, with quite large P values. The dominant leg of the healthy group is therefore suitable for use as a comparator for all between group analyses.

The healthy group displayed high levels of symmetry with no significant differences in performance between dominant and non dominant limbs. The dominant limb offers a slightly higher target and is therefore selected as the comparator limb for all further activity analysis. The between groups analysis for the activity parameters will now be presented.

Table 36: Differences between limbs in hop distance in healthy subjects; there were no significant differences.

leg	mean	SE	statistic	sig.	Mean diff	SE	95% CI lower	95% CI upper
dom	0.89	0.02	t = .511	.611	.00	.01	-.01	.02
non	0.88	0.02						

Key: Hop distance is normalised to height (hop distance (m) / height (m)), dom = dominant leg, non = non dominant leg, SE = standard error of the mean, ES = effect size, mean diff = mean difference, CI = Confidence interval.

Gait

Descriptive and inferential statistics are displayed in Table 37 and 38. Weight was a significant covariate for gait velocity and was therefore included in the analysis. On average, ACLD subjects walked more slowly than healthy subjects; this difference was statistically significant; the mean difference of 0.14 m/s represents an average functional deficit of 10% compared to healthy people. Gait velocity was a significant covariate for all the gait strategy parameters with large effect sizes (ES>0.5) and was therefore included in the analysis. Correlations are displayed in Table 39. There were no significant differences between the groups in any of the strategy parameters. Gait velocity alone therefore demonstrates the differences between the groups; there is a trend that symmetry might add to that, though this is not significant.

The clinical significance criteria (>1 SD below healthy mean for failure to recover and <0.5SD below healthy mean for full recovery) were set as follows: failure to recover < 1.26m/s, partial recovery 1.26m/s to 1.325m/s and full recovery > 1.325m/s. On these criteria, 44 failed to recover, 8 partially recovered and 22 ACLD subjects are considered to have recovered a healthy gait velocity prior to surgery.

Table 37: Exploration of gait velocity and subjects weight as covariates for ACLD and Healthy group differences in gait parameters; gait velocity and weight are significant covariates.

parameter	group	mean	SD	gait velocity (m/s)			weight (kg)		
				statistic	sig.	ES	statistic	sig.	ES
velocity	H	1.39	0.13				F = 4.7	.032	.03
	ACLD	1.23	0.19						
cadence	H	112	6.6	F = 137.2	<.001	.52	F = 16.6	<.001	.13
	ACLD	106	8.3						
SLI	H	0.73	0.1	F = 356.6	<.001	.73	F = 12.6	.001	.09
	ACLD	0.68	0.1						
SLN	H	0.75	0.1	F = 301.9	<.001	.70	F = 8.1	.005	.06
	ACLD	0.69	0.1						
symm	H	98	3.8	F = 4.8	.030	.04	F = 0.8	.386	.01
	ACLD	99	7.3						

Key: velocity (m/s), cadence (steps / minute), SLI = step length injured (m), SLN = step length non-injured (m), symm = step length symmetry (% uninjured leg), H = healthy, ACLD = anterior Cruciate ligament deficient, SD = standard deviation, ES = Effect size.

Table 38: Differences in Gait parameters between ACLD and Healthy groups; there were significant differences only in gait velocity (highlighted in greyscale).

parameter	group	mean	SE	paired differences						
				statistic	sig.	ES	mean diff	SE	95% CI	
									lower	upper
velocity	H	1.38	0.02	F = 20.489	<.001	.14	-0.14	.03	0.08	0.20
	ACLD	1.24	0.02							
cadence	H	109	0.7	F = 0.228	.634	.00	0.5	1.0	-2.5	1.5
	ACLD	109	0.7							
SLI	H	0.70	0.0	F = 0.469	.495	.02	-0.0	0.0	-0.0	0.0
	ACLD	0.71	0.0							
SLN	H	0.72	0.0	F = 1.225	.270	.01	0.0	0.0	-0.0	0.0
	ACLD	0.71	0.0							
symm	H	98	0.8	F = 2.718	.072	.10	-1.9	1.1	-3.9	0.2
	ACLD	99	0.7							

Key: velocity (m/s), cadence (steps / minute), SLI = step length injured (m), SLN = step length non-injured (m), symm = step length symmetry (% uninjured leg), SE = Standard error of the mean, mean diff = mean difference, CI = confidence interval, ES = Effect size = Partial Eta Squared. **Note:** step length symmetry is a bootstrap mean difference due to breach of the assumption of homogeneity of variance, Levenes F(1, 133) = 40.381, P <0.001. ES = Partial Eta Squared.

Table 39: Correlations between the gait parameters for the ACLD group; gait velocity is strongly correlated to the other parameters.

parameter	velocity	cadence	SLI	SLN
velocity	1	.603**	.795**	.749**
cadence	.603**	1	.020	-.033
SLI	.795**	.020	1	.901**
SLN	.749**	-.033	.901**	1

Key: velocity (m/s), cadence (steps / minute), SLI = step length injured (m), SLN = step length non-injured (m), correlation coefficient is r, ** Significant at P<0.001.

Single Leg Squat

Descriptive and inferential statistics are displayed in Table 40 and 41. Weight was not a significant covariate for squat repetitions on either limb of the ACLD subjects; however it was a significant covariate for squat depth on both limbs and was therefore included in this analysis. On average, ACLD subjects performed fewer squat repetitions than healthy subjects on both limbs. This difference is statistically significant for both; the mean difference of 14 reps on the injured limb represents a functional deficit of 67%, and 11 reps on the non-injured limb a deficit of 52%. In the healthy group 48 (79%) lost balance and 13 stopped due to other reasons. In the ACLD group there were 49 (66%) who lost balance and 25 that stopped for other reasons. There was no significant difference in the number of squat repetitions completed (t(72) = -1.605, P = 0.133); the VAS (t(72)= 1.210, P = 0.230); or IKDC SKF (t(72) = 1.284, P = 0.203) between those who stopped and those who lost balance. On average, ACLD subjects squatted with less knee bend than healthy subjects on both limbs. However, this difference is statistically significant only for the injured limb; the mean difference of 12 degrees (95% CI 6-18) represents a functional deficit of 13%.

The clinical significance criteria were set at failure to recover > 105 degrees, partial recovery 97.5 to 105 degrees and full recovery < 97.5 degrees. On these criteria 40 subjects failed to recover, 10 partially recovered and 24 (32%) recovered within healthy squat depth performance prior to surgery.

Table 40: Exploration of subject's weight as a covariate for ACLD and healthy group differences in squat parameters on each limb; weight is a significant covariate for squat depth but not squat repetitions.

<table>
<tr><th>squat parameter</th><th>group</th><th>leg</th><th>mean</th><th>SD</th><th>statistic</th><th>sig.</th><th>ES</th></tr>
<tr><td rowspan="4">repetitions</td><td>H</td><td rowspan="2">inj</td><td>21</td><td>12</td><td rowspan="2">F = .764</td><td rowspan="2">.384</td><td rowspan="2">.01</td></tr>
<tr><td>ACLD</td><td>7</td><td>5</td></tr>
<tr><td>H</td><td rowspan="2">non</td><td>21</td><td>12</td><td rowspan="2">F = .812</td><td rowspan="2">.369</td><td rowspan="2">.01</td></tr>
<tr><td>ACLD</td><td>10</td><td>8</td></tr>
<tr><td rowspan="4">depth</td><td>H</td><td rowspan="2">inj</td><td>90</td><td>15</td><td rowspan="2">F = 12.607</td><td rowspan="2">.001</td><td rowspan="2">.09</td></tr>
<tr><td>ACLD</td><td>106</td><td>17</td></tr>
<tr><td>H</td><td rowspan="2">non</td><td>90</td><td>15</td><td rowspan="2">F = 8.189</td><td rowspan="2">.005</td><td rowspan="2">.06</td></tr>
<tr><td>ACLD</td><td>97</td><td>14</td></tr>
</table>

Key: repetitions (number), depth (°), H = healthy, ACLD = anterior Cruciate deficient, inj = Injured leg, non = non-injured leg, SD = standard deviation, ES = effect size.

Table 41: Differences in squat parameters between the ACLD and Healthy groups; there were significant differences in squat repetitions on both legs and squat depth only on the injured leg (highlighted in greyscale).

param	leg	group	mean	SE	statistic	sig.	ES	mean diff	SE	95% CI lower	95% CI upper
reps	inj	ACLD	7	0.7	t = 9.623	<.001	.64	-14	1.6	-17	-11
		H	21	1.6							
	non	ACLD	10	1.0	t = 6.538	<.001	.49	-11	1.8	-14	-7
		H	21	1.6							
depth	inj	ACLD	103	1.9	F = 17.380	<.001	.12	12	2.9	6	18
		H	92	2.1							
	non	ACLD	95	1.9	F = 2.443	.123	.02	4	2.6	1	9
		H	92	2.1							

Key: reps = squat repetitions (number), depth = peak knee flexion (°), inj = injured leg, non = non-injured leg. SE = Standard error of the mean, mean diff = mean difference, CI = confidence interval, ES = Effect size = Partial Eta Squared. Bootstrap statistics are supplied for injured squat reps and non-injured squat depth.

Squat symmetry: between limb differences in the ACLD group

Descriptive and inferential statistics are displayed in Table 42 and 43. Weight was a significant covariate for squat repetitions and was included in the analysis. Unlike the healthy group who demonstrated symmetrical performance, there were significant differences between limbs in the ACLD group. On average, the ACLD group performed fewer squat repetitions on their injured leg. This difference was statistically significant; the mean difference of 3 repetitions represents a functional deficit of 30% on the injured limb. On average, the ACLD group squatted more deeply on the non-injured leg. This difference was statistically significant; the mean difference of 9 degrees represents a functional deficit of 9%.

Table 42: Exploration of weight as a covariate for between limb differences in squat parameters for the ACLD subjects; weight is a significant covariate for squat repetitions but not squat depth.

Parameter	leg	mean	SD	statistic	sig.	ES
repetitions	inj	7	5	F = 8.762	.004	.00
	non	10	8			
depth	inj	106	19	F = 14.642	<.001	.09
	non	97	14			

Key: repetitions (number), depth = peak knee flexion (°), inj = injured leg, non = non-injured leg, SD = Standard deviation, ES = Effect size.

Table 43: Between limb differences for squat repetitions and squat depth for the ACLD subjects; there were significant differences with poorer performance on the injured limb.

parameter	leg	mean	SE	statistic	sig.	ES	mean diff	95% CI	
								lower	upper
repetitions	inj	7	0.8	F = 8.672	.004	.06	-3	-5	-1
	non	10	0.8						
depth	inj	106	1.8	F = 12.882	<.001	.08	9	4	14
	non	97	1.8						

Key: Reps = squat repetitions (number), Depth = peak knee flexion (°), Inj = injured leg, Non = non-injured leg, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

Hop for Distance

Descriptive and inferential statistics are displayed in Table 44. On average, the ACLD subjects hopped less far than healthy subjects on both the injured and non-injured limbs. These differences were statistically significant; the mean difference represents a functional deficit of 31% on the injured limb and 19% on the non-injured limb. The clinical significance criteria were set at below 0.76 for failure to recover, 0.76 to 0.825 for partial recovery and above 0.825 for full recovery. On these criteria 57 have failed to recover, 7 were partially recovered and 10 subjects are considered to have recovered a healthy hop distance prior to surgery.

Table 44: Differences in hop distance between ACLD and Healthy groups; there were significant differences with ACLD subjects hopping less far on both injured and non-injured legs (highlighted in greyscale).

leg	group	mean	SD	SE	statistic	sig.	ES	mean diff	SE	95% CI	
										lower	upper
inj	H	.89	.13	.02	t = 10.206	<.001	.65	.28	.03	.23	.34
	ACLD	.61	.18	.02							
non	H	.89	.13	.02	t = 6.248	<.001	.48	.17	.03	.12	.22
	ACLD	.72	.18	.02							

Key: Hop distance is normalised to height, Inj = injured leg, Non = non-injured leg, H = healthy subjects, ACLD = Anterior cruciate ligament deficient subjects, M = Mean, SD = Standard deviation, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

Hop Symmetry

Descriptive and inferential statistics for between limb differences in hop distance are displayed in Table 45. Unlike the healthy group who demonstrated no significant difference between limbs, the ACLD group demonstrated a significantly (t = -6.286, P <.001) shorter hop for the injured leg than the non-injured. The mean difference was .11 x height (95% CI = .07 to .14) which represents a 15% functional deficit compared to the uninjured limb.

Table 45: Between limb differences in hop distance for the ACLD subjects; there were significant differences with poorer performance on the injured limb

group	leg	mean	SE	statistic	sig.	mean diff	SE	95% CI	
								lower	upper
ACLD	inj	.61	.19	t = -6.286	.000	-.11	.02	-.14	-.07
	non	.72	.18						

Key: Hop distance is normalised to height, ACLD = Anterior cruciate ligament deficient subjects, inj = injured leg, non = non-injured leg, SD = Standard deviation, SE = Standard error of the mean, mean diff = mean difference, CI = confidence interval, ES = Effect size.

Descriptive statistics for hop performance on the basis of LSI are presented in Table 46. On average, healthy subjects were more symmetrical in hop distance than ACLD subjects. This difference was statistically significant (t = 4.915, P <0.001, r = 0.46), the mean difference was

14% (95% CI = 8 to 20). The application of LSI criteria demonstrates that 95% of the healthy subjects are within the 90% LSI criteria. Only 26% of healthy subjects meet this criterion and 47% fail to meet the lowest symmetry criteria (85%) The ACLD group are more asymmetrical with greater numbers failing to meet all the LSI standards. In order to explore the relationship between symmetry and performance, differences in hop distance between the healthy and ACLD groups that passed the 85% criteria was performed. This demonstrated a significant difference ($t(95) = 5.911$, $P < 0.001$, ES = 0.52) in hop distance such that healthy group (mean = 0.89, SE = 0.02) performed better than the ACLD group (M = 0.71, SE = 0.03). The mean difference of 0.18 represents a performance deficit of 20% in a group that might have been considered recovered on LSI criteria. The mean LSI in the healthy group is 101% with a SD of 7%, the clinical significance criteria are therefore set at < 0.94 for failure to recover, 0.94 to 0.975 for partial recovery and 0.975 for full recovery. These criteria are much higher than those traditionally applied and it is therefore no surprise that on these criteria fewer of the ACLD subjects were classified as recovered: 52 were not recovered, 5 partially recovered and 17 fully recovered. The data clearly demonstrates that healthy subjects were symmetrical in their hop performance and that the 85% LSI criteria is too low to reflect healthy performance. The application of the clinical significance criteria suggests that the more recently recommended (Thomeé et al., 2012) 95% LSI criterion is very close to being representative of the healthy mean minus 1 SD and may therefore be a better criteria.

Table 46: Distribution of hop distance LSI in healthy and ACLD subjects and frequency distribution at each of the published Hop Limb Symmetry Index (LSI) criteria; ACLD subjects are more asymmetrical and a greater number fail the more rigorous LSI criteria.

	ACLD		Healthy	
mean (SD)	**0.87 (0.24)**		**1.01 (0.7)**	
LSI	**n**	**%**	**n**	**%**
<85%	**35**	**47**	**0**	**0**
85% - 90%	**9**	**12**	**3**	**5**
90%- 95%	**10**	**14**	**6**	**10**
95%- 100%	**20**	**27**	**52**	**85**

Key: ACLD = Anterior cruciate ligament deficient subjects, SD = standard deviation, LSI = Limb symmetry index, n = number of subjects.

Hop strategy – 2D TIP

Descriptive and inferential statistics are displayed in Table 47 and 48. Hop distance was a significant covariate for all of the TIP angle parameters and for the TIP length change parameter and was therefore included in these analyses. On average, ACLD subjects landed with longer TIP length at initial contact, longer TIP length at PKF and used less change in TIP length before PKF. These differences were all statistically significant and represent a less telescopic strategy in the ACLD group. There was also a significant interaction effect for phase and group ($F1,132$) = 3.964, $P = 0.049$, Partial Eta squared = 0.03), the interaction plot in Figure 26 demonstrates the significant difference at IC and PKF and that the slope of the change is different between groups. The plot clearly shows that on average the ACLD group not only used a less pendular strategy with a longer TIP length at IC and throughout the landing phase, this might represent a straighter knee or more upright trunk at IC and less movement at either or both between the phases. The changes at IC suggest the presence of an adapted strategy. On average, there is no significant difference in TIP angle at IC. However ACLD subjects did land with lower TIP angle at PKF and less change in TIP angle between the phases, these differences were statistically significant and represent a less pendular strategy in the ACLD group. There was also a significant interaction between phase and group ($F(1,132) = 13.006$, $P < 0.001$, Partial Eta Squared = 0.09), the interaction plot in Figure 26 clearly demonstrates the lack of a significant difference in TIP angle at IC, however the interaction splays out between phases with a steeper change in the healthy subjects. The ACLD subjects were limiting the forward progression of TIP angle, suggesting a stiffer knee and more upright trunk position.

In combination, this data is evidence of a different landing strategy on the injured limb of ACLD subjects that combines less change in TIP length and TIP angle. The model does not allow us to understand where this difference is occurring, so analysis of the kinematic parameters is required to further explore this.

Table 47: Exploration of hop distance as a covariate for the Telescopic Inverted pendulum (TIP) landing strategy parameters; hop distance is a significant covariate (greyscale).

TIP parameter		group	mean	SD	statistic	sig.	ES
TIP length (%LL)	IC	H	111	3	F = 0.794	.374	.01
		ACLD	116	6			
	PKF	H	97	6	F = 3.841	.052	.03
		ACLD	108	8			
	Change	H	13	5	F = 13.290	<.001	.09
		ACLD	9	5			
TIP angle (°)	IC	H	73	3	F = 204.705	<.001	.61
		ACLD	79	5			
	PKF	H	84	3	F = 33.492	<.001	.20
		ACLD	84	6			
	Change	H	12	4	F = 6.621	.011	.05
		ACLD	6	6			

Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Change = change between phases, H = Healthy subjects, ACLD = Anterior Cruciate Ligament Deficient subjects, M = Mean, SD = Standard deviation, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

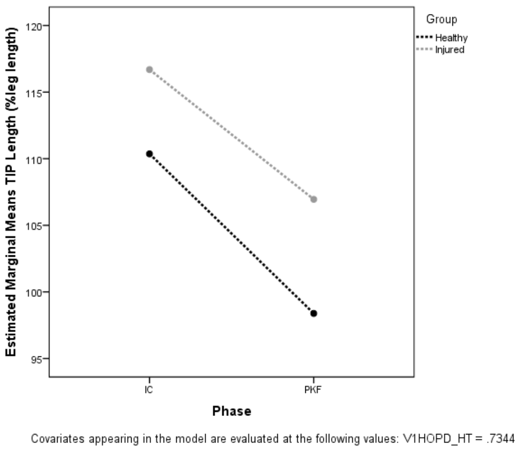
Table 48: Differences in TIP parameters between ACLD and Healthy groups; there were significant differences in all but one parameter (highlighted in greyscale).

TIP parameter		group	mean	SE	statistic	ES	mean diff	SE	sig.	95%CI	
										lower	upper
TIP length (%LL)	IC	H	111	0.4	t = -7.031	.52	6	0.8	<.001	4	7
		ACLD	116	0.6							
	PKF	H	97	0.8	t = -8.599	.69	11	1.2	<.001	8	13
		ACLD	108	0.9							
	Ch	H	12	0.8	F = 3.964	.03	-2	1.1	.049	0	5
		ACLD	10	0.7							
TIP angle (°)	IC	H	76	0.4	F = 1.340	.00	0	0.5	.625	-1	1
		ACLD	76	0.4							
	PKF	H	86	0.7	F = 12.133	.08	-4	1.1	.001	-2	-6
		ACLD	83	0.6							
	Ch	H	11	0.7	F = 13.006	.09	-4	1.2	.002	-2	-6
		ACLD	7	0.6							

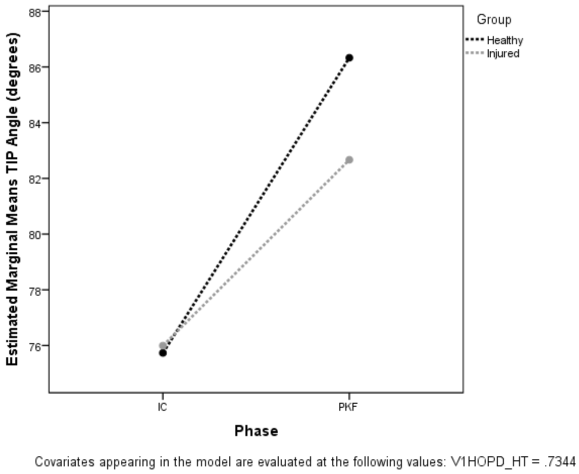
Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Change = change between phases, H = Healthy, ACLD = Anterior Cruciate Ligament Deficient, M = Mean, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size. **Note:** TIP angle at IC and TIP angle change are bootstrap statistics due to violation of the assumption of homogeneity of variances, Levenes F(1,133) = 8.531, P = 0.004 and F (1,133) = 4.725, P = 0.032 and respectively.

Figure 26: Interaction plots for phase (IC and PKF on x axis) and group (ACLD in grey and Healthy in black) for the TIP parameters; there were significant interactions, TIP length is different at both phases with similar gradient between phases, TIP angle is similar at initial contact with different gradients approaching peak knee flexion.

TIP length (% leg length)



TIP angle (°)



Hop Strategy - Kinematics

Descriptive and inferential statistics are displayed in Table 49 and 50. Hop distance was a significant covariate only for knee flexion at IC and was therefore included as a covariate for this parameter only. On average, ACLD subjects had a straighter knee and more upright trunk at IC; however these differences were not significant. This finding is consistent with the hypothesis that came from the previously identified increase in TIP length at IC. The lack of statistical significance in the kinematic parameters offers further evidence that by utilising whole body mechanics, the TIP model is demonstrating differences in strategy that may not be identified in the kinematic parameters alone. On average, the ACLD subjects used 13 degrees less knee flexion excursion and 8 degrees less trunk lean excursion before PKF, where ACLD subjects ended with a straighter knee and less forward trunk lean. All of these differences are statistically significant. Again, this agrees with the expectations derived from the TIP model and explains the reduced excursion seen in those parameters.

The Interaction terms between phase and group (Figure 27) were significant for both knee flexion ($F(1,132) = 18.498$, $P < .001$, Partial Eta Squared = 0.123) and trunk lean $F(1,132)$ – 15.504, $P < .001$, Partial Eta Squared = 0.150) indicating different strategies in the ACLD subjects at both body segments. The interaction plots show that whilst the knee flexion is similar at IC, the trunk lean has reduced. Both plots demonstrate flatter slopes in the ACLD group, confirming a stiffer strategy with less knee joint excursion. This is however more marked for trunk lean, where the slope is negative in the ACLD group, indicating a backward lean, and positive in the healthy group indicating forward lean. This trunk position explains both the greater TIP length throughout the motion and the reduction in TIP angle change as the COG is prevented from progressing forward over the stance limb.

Table 49: Exploration of hop distance as a covariate for ACLD and Healthy group differences in the landing strategy kinematic parameters; hop distance is a significant covariate for knee flexion at initial contact.

parameter		group	mean	SD	statistic	sig.	ES
knee flexion (°)	**IC**	**H**	29	5	F = 4.048	.046	.03
		ACLD	28	11			
	PKF	**H**	64	11	F = 3.682	.057	.03
		ACLD	50	12			
	Change	**H**	34	10	F = 0.164	.686	.00
		ACLD	22	13			
trunk lean (°)	**IC**	**H**	12	7	F = 0.800	.373	.01
		ACLD	10	8			
	PKF	**H**	19	12	F = 1.330	.251	.01
		ACLD	9	11			
	Change	**H**	7	8	F = 0848	.359	.01
		ACLD	-1	7			

Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, H = Healthy, ACLD = Anterior Cruciate Ligament Deficient, M = Mean, SD = Standard deviation ES = Effect size.

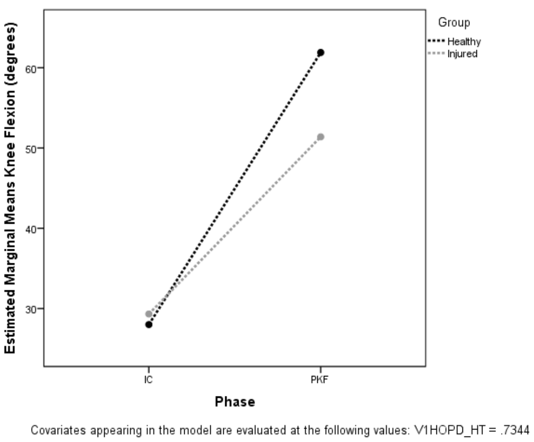
Table 50: Differences in kinematic parameters during Hop landing between ACLD and Healthy subjects; there were significant differences in knee flexion and trunk lean at PKF and in the change between phases (highlighted in greyscale), with greater excursion in the Healthy group.

parameter		group	mean	SE	statistic	sig.	ES	mean diff	SE	95%CI lower	95%CI upper
knee flexion (°)	IC	H	28	1.3	F = 0.454	.525	.00	1	1.9	-5	3
		ACLD	29	1.2							
	PKF	H	64	1.5	t = 6.837	<.001	.51	-14	2.0	-17	-10
		ACLD	50	1.4							
	Change	H	34	1.3	t = 6.027	<.001	.72	-13	2	-17	-8
		ACLD	22	1.6							
trunk lean (°)	IC	H	12	.9	t = 1.632	.105	.14	-2	1.3	-5	0
		ACLD	10	.9							
	PKF	H	19	1.6	t = 4.825	<.001	.39	-10	2	-14	-6
		ACLD	9	1.3							
	Change	H	7	1.0	t = 5.974	<.001	.46	-8	1.3	-10	-5
		ACLD	-1	0.8							

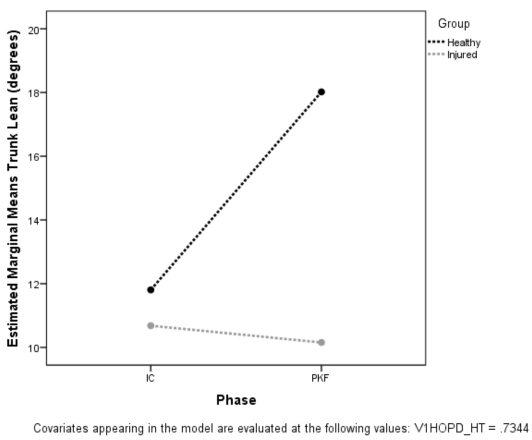
Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, H = Healthy, ACLD = Anterior Cruciate Ligament Deficient, M = Mean, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size. **Note:** Bootstrap statistics are presented for knee flexion IC and trunk lean change.

Figure 27: Interaction plots for phase (IC and PKF on x axis) and group (ACLD in grey and Healthy in black) for the kinematic parameters during hop landing; both parameters are similar at IC but the differing gradients indicate altered strategy, with greater knee flexion and forward trunk lean in the healthy subjects.

knee flexion (°)



trunk lean (°)



In summary, an altered landing strategy has been identified for the injured limb of ACLD subjects. This strategy is characterised by functional stiffness, reducing both the pendular and telescopic motion of the COG by adopting a more upright trunk position and straighter knee whilst limiting excursion of both before PKF. The performance data demonstrates bilateral deficits in hop distance and it will therefore be useful to understand whether strategy is also affected bilaterally. The analysis was therefore repeated on the non-injured leg.

Hop strategy on the non-injured limb – 2D TIP

Descriptive and inferential statistics are displayed in Table 51 and 52. Hop distance was a significant covariate for all parameters with the exception of TIP length at IC and was therefore included as a covariate in the analysis. There were significant differences in TIP length at both IC and PKF and in TIP angle at PKF. Both change variables were significantly different and there were significant interaction terms for both TIP length ($F(1,132) = 4.052$, $P = 0.046$, Partial Eta Squared = 0.03) and TIP angle ($F(1,132) = 4.062$, $P = 0.046$, Partial Eta Squared = 0.030). The differences are again seen in the interaction plots (Figure 28) although the difference in gradient is much more subtle. The ACLD subjects were therefore also adopting a significantly different strategy to the healthy subjects on the non-injured limb. On average, they were landing with a longer TIP length throughout the landing and with less change in TIP angle. This is the same strategy as was demonstrated on the injured limb, the differences from healthy were however smaller.

Table 51: Exploration of hop distance as a covariate for differences between ACLD and healthy in TIP parameters when landing on the non-injured leg; Hop distance is a significant covariate for all parameters except TIP length at IC.

<table>
<tr><th colspan="2">TIP parameter</th><th>group</th><th>mean</th><th>SD</th><th>statistic</th><th>sig.</th><th>ES</th></tr>
<tr><td rowspan="6">TIP length (%LL)</td><td rowspan="2">IC</td><td>H</td><td>111</td><td>3</td><td rowspan="2">F = .273</td><td rowspan="2">.602</td><td rowspan="2">0.02</td></tr>
<tr><td>ACLD</td><td>115</td><td>4</td></tr>
<tr><td rowspan="2">PKF</td><td>H</td><td>98</td><td>6</td><td rowspan="2">F = 23.111</td><td rowspan="2"><.001</td><td rowspan="2">0.15</td></tr>
<tr><td>ACLD</td><td>107</td><td>8</td></tr>
<tr><td rowspan="2">Change</td><td>H</td><td>13</td><td>5</td><td rowspan="2">F = 38.287</td><td rowspan="2"><.001</td><td rowspan="2">0.225</td></tr>
<tr><td>ACLD</td><td>8</td><td>6</td></tr>
<tr><td rowspan="6">TIP angle (°)</td><td rowspan="2">IC</td><td>H</td><td>73</td><td>3</td><td rowspan="2">F = 358.021</td><td rowspan="2"><.001</td><td rowspan="2">0.73</td></tr>
<tr><td>ACLD</td><td>76</td><td>4</td></tr>
<tr><td rowspan="2">PKF</td><td>H</td><td>84</td><td>3</td><td rowspan="2">F = 7.225</td><td rowspan="2">.008</td><td rowspan="2">0.05</td></tr>
<tr><td>ACLD</td><td>83</td><td>4</td></tr>
<tr><td rowspan="2">Change</td><td>H</td><td>12</td><td>4</td><td rowspan="2">F = 61.362</td><td rowspan="2"><.001</td><td rowspan="2">0.32</td></tr>
<tr><td>ACLD</td><td>7</td><td>4</td></tr>
</table>

Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Change = change between phases, H = Healthy, ACLD = Anterior Cruciate Ligament Deficient, M = Mean, SD = Standard deviation, ES = Effect size.

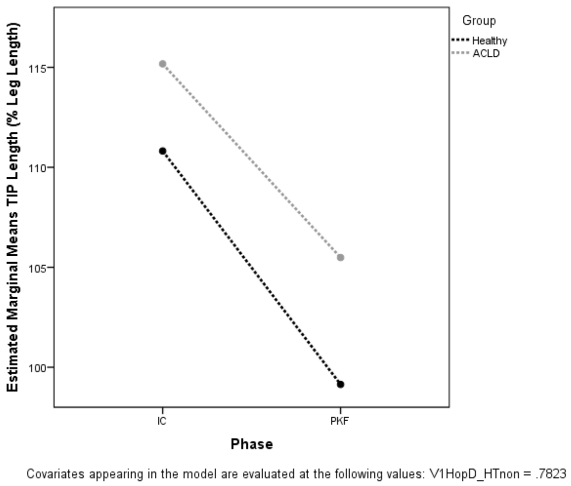
Table 52: Differences in TIP parameters between ACLD (non injured limb) and Healthy subjects during hop landing; there were significant differences with the injured subjects demonstrating a stiffer landing strategy.

<table>
<tr><th colspan="2" rowspan="2">TIP parameter</th><th rowspan="2">group</th><th rowspan="2">mean</th><th rowspan="2">SE</th><th rowspan="2">statistic</th><th rowspan="2">sig.</th><th rowspan="2">ES</th><th rowspan="2">mean diff</th><th rowspan="2">SE</th><th colspan="2">95%CI</th></tr>
<tr><th>lower</th><th>upper</th></tr>
<tr><td rowspan="6">TIP length (%LL)</td><td rowspan="2">IC</td><td>H</td><td>111</td><td>.5</td><td rowspan="2">t = 7.440</td><td rowspan="2"><.001</td><td rowspan="2">.54</td><td rowspan="2">5</td><td rowspan="2">0.6</td><td rowspan="2">3</td><td rowspan="2">6</td></tr>
<tr><td>ACLD</td><td>115</td><td>.4</td></tr>
<tr><td rowspan="2">PKF</td><td>H</td><td>99</td><td>.9</td><td rowspan="2">F = 22.137</td><td rowspan="2"><.001</td><td rowspan="2">.14</td><td rowspan="2">6</td><td rowspan="2">1.3</td><td rowspan="2">4</td><td rowspan="2">9</td></tr>
<tr><td>ACLD</td><td>105</td><td>.8</td></tr>
<tr><td rowspan="2">Ch</td><td>H</td><td>12</td><td>.7</td><td rowspan="2">F = 4.052</td><td rowspan="2">.046</td><td rowspan="2">.03</td><td rowspan="2">2</td><td rowspan="2">1.0</td><td rowspan="2">0</td><td rowspan="2">4</td></tr>
<tr><td>ACLD</td><td>10</td><td>.6</td></tr>
<tr><td rowspan="6">TIP angle (°)</td><td rowspan="2">IC</td><td>H</td><td>75</td><td>.3</td><td rowspan="2">F = 1.482</td><td rowspan="2">.226</td><td rowspan="2">.01</td><td rowspan="2">0</td><td rowspan="2">0.4</td><td rowspan="2">0</td><td rowspan="2">1</td></tr>
<tr><td>ACLD</td><td>74</td><td>.2</td></tr>
<tr><td rowspan="2">PKF</td><td>H</td><td>84</td><td>.5</td><td rowspan="2">F = 6.366</td><td rowspan="2">.013</td><td rowspan="2">.05</td><td rowspan="2">2</td><td rowspan="2">0.7</td><td rowspan="2">0</td><td rowspan="2">3</td></tr>
<tr><td>ACLD</td><td>83</td><td>.5</td></tr>
<tr><td rowspan="2">Ch</td><td>H</td><td>10</td><td>.5</td><td rowspan="2">F = 4.062</td><td rowspan="2">.046</td><td rowspan="2">.03</td><td rowspan="2">1</td><td rowspan="2">0.7</td><td rowspan="2">0</td><td rowspan="2">3</td></tr>
<tr><td>ACLD</td><td>9</td><td>.4</td></tr>
</table>

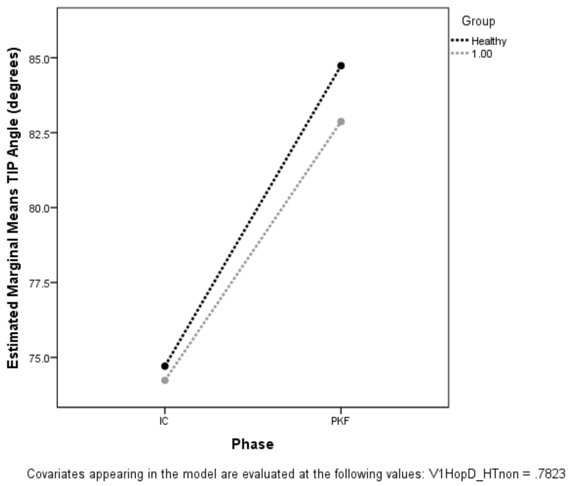
Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Change = change between phases, H = Healthy, ACLD = Anterior Cruciate Ligament Deficient, M = Mean, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

Figure 28: Interaction plots for phase (IC and PKF on x axis) and group (ACLD in grey and Healthy in black) for TIP parameters when landing on the non-injured leg; differences between phases and in gradient are similar to the injured limb but much more subtle.

TIP length (% leg length)



TIP angle (°)



Hop strategy on the non-injured limb – Kinematics

Descriptive and inferential statistics are displayed in Table 53 and 54. Hop distance was a significant covariate for all kinematic variables and was therefore included as a covariate in all analyses. There were no significant differences in kinematic parameters at IC, however both parameters were significantly different at PKF and in the change variable. This is reflected in the significant interaction terms for both knee flexion ($F(1,132) = 6.037$ $P = 0.015$, Partial Eta squared = 0.044), trunk lean ($F(1,132) = 13.581$, $P < 0.001$, Partial Eta squared = 0.093. Whilst the knee interaction is significant the trunk lean interaction is considerably larger (Figure 29), demonstrating the same strategy that was identified on the non-injured limb, again with smaller effect.

Table 53: Exploration of hop distance as a covariate for ACLD (non-injured limb) and healthy group differences in kinematic parameters; hop distance was a significant covariate.

parameter		group	mean	SD	statistic	sig.	ES
knee flexion (°)	IC	H	29	5	F = 13.703	.001	.09
		ACLD	25	7			
	PKF	H	64	11	F = 24.143	<.001	.15
		ACLD	51	13			
	Change	H	34	10	F = 11.262	.001	.08
		ACLD	25	11			
trunk lean (°)	IC	H	12	7	F = 7.275	.008	.05
		ACLD	9	8			
	PKF	H	19	12	F = 13.467	<.001	.09
		ACLD	7	14			
	Change	H	7	8	F = 12.213	.001	.09
		ACLD	-2	8			

Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, H = Healthy, ACLD = Anterior Cruciate Ligament Deficient, SD = Standard deviation, ES = Effect size.

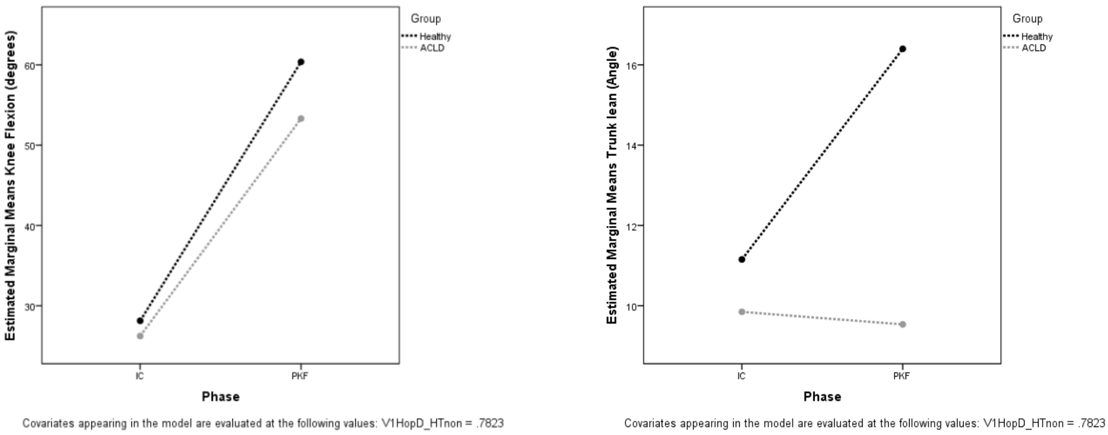
Table 54: Differences in kinematics between ACLD (non-injured limb) and Healthy subjects during Hop landing; there were significant differences at PKF and in the change variable (highlighted in greyscale) indicating a stiffer landing strategy.

parameter		group	mean	SE	statistic	ES	mean diff	SE	sig.	95%CI	
										lower	upper
knee flexion (°)	IC	H	28	0.8	F = 2.529	.02	2	1.1	.114	0	4
		ACLD	26	0.7							
	PKF	H	60	1.6	F = 9.149	.06	7	2.3	.003	2	12
		ACLD	53	1.4							
	Change	H	32	1.5	F = 6.037	.04	5	2.1	.015	1	9
		ACLD	27	1.3							
trunk lean (°)	IC	H	11	1.0	F = 0.725	.05	1	1.5	.396	-2	4
		ACLD	10	.9							
	PKF	H	16	1.8	F = 7.173	.39	7	2.6	.008	2	12
		ACLD	10	1.6							
	Change	H	5	1.0	F = 13.581	.46	6	1.5	<.001	2	9
		ACLD	0	0.9							

Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, H = Healthy, ACLD = Anterior Cruciate Ligament Deficient, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

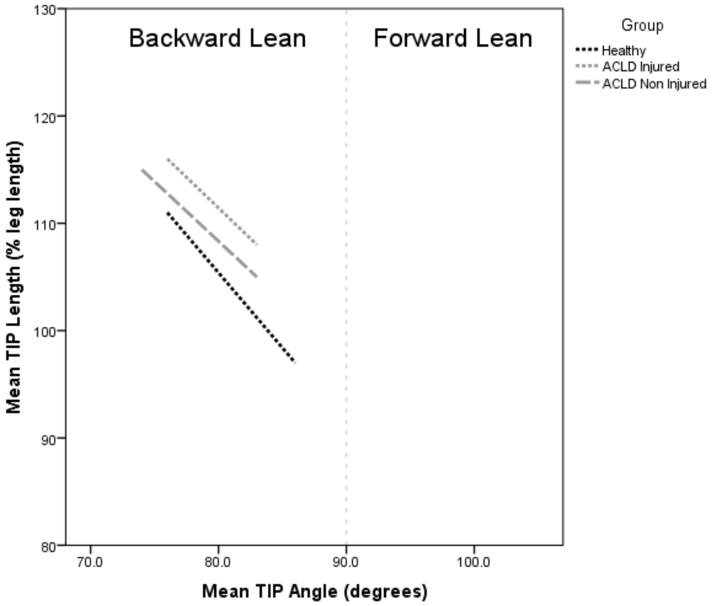
Figure 29: Interaction plots for phase (IC and PKF on x axis) and group (ACLD in grey and Healthy in black) for Kinematic parameters during hop landing on the non-injured leg; knee flexion follows similar gradient, however trunk lean shows a significant difference in gradient with greater forward trunk lean at PKF in the Healthy subjects.

knee flexion (°) **trunk lean (°)**



There is evidence of a bilateral adaptation in landing strategy. The strategy is similar for both legs, however the non-injured leg is less affected than the injured limb. This is demonstrated in Figure 30 where the TIP parameters are plotted against each other to represent the COG motion between phases. The healthy subjects had a longer, steeper trajectory; the ACLD subjects a shorter flatter trajectory for both legs. The most important finding is that of a stiffer strategy with a longer TIP length, reduced knee flexion and forward trunk lean. This average strategy is clearly adapted; however there is considerable variation in all the parameters. Further analysis is required to explore any sub grouping of strategy that may exist within the ACLD subjects.

Figure 30: Plot of TIP length (y axis) against TIP angle (x axis) demonstrating bilateral adaptation of landing strategy in the ACLD group. There were significant differences in TIP strategy between the healthy subjects (black line) and both the injured (grey small dash line) and non-injured (grey large dash line) legs of the ACLD subjects.



Are there different strategies within ACLD subjects?

The TIP change parameters consistently showed significant differences between groups and were therefore used as the primary variables to define landing strategy in the ACLD subjects. Clinical significance criteria for each TIP parameter were used to split the ACLD group into two subsets, those with a stiffer than healthy TIP strategy (Stiff) or healthy TIP strategy at 0.5SD below the healthy mean (Table 55). There were 51 who had TIP change parameters below healthy values and were classified stiff, the remaining 23 had recovered at least one TIP parameter within healthy values and were classified healthy. Eight subjects were within healthy for both TIP parameters. Amongst those that recovered there were 11 who had attended rehabilitation and 12 who had not. The subgroups were significantly different for hop distance with those with the healthy strategy having a significantly longer hop distance, suggesting that strategy and performance are linked. As expected the subgroups were also significantly different for the TIP variables, there were significant interaction effects between subgroup and phase (TIP L $F(2,70) = 102.166$ $P < 0.001$, Partial Eta Squared = 0.59) TIP A $F(2,70) = 12.244$ $P = 0.001$, Partial Eta Squared = 0.15). The steeper gradient in the interaction plots (Figure 31) for those with recovery of TIP parameters clearly demonstrates the softer landing with greater telescopic and pendular action. The lower gradient indicates a stiffer landing in those who have not recovered TIP parameters. On average, there were significant differences in knee flexion at PKF and the change variable but not knee flexion at IC, which is demonstrated by a significant interaction effect of subgroup and phase ($F(2,70) = 18.457$ $P < 0.001$, Partial Eta Squared = 0.21) and in the interaction plots as the lines separate out between phases. Those that had a healthy TIP strategy utilise greater knee flexion. On average the trunk lean parameters were significantly different between subgroups at both IC and PKF, however there was no significant difference in the change score and no significant interaction between subgroup and phase ($F(2,70) = 1.585$ $P = 0.212$, Partial Eta Squared = 0.22). This is demonstrated in the interaction plot (Figure 31) where the lines run parallel, with the healthy subgroup showing greater forward trunk lean throughout the landing phase. Those that have a healthy hop strategy therefore utilise a greater forward trunk lean throughout the landing, which was not seen within the healthy subjects. This appeared to be an adaptation aimed at maintaining COG motion within healthy limits, possibly to compensate for increased functional knee stiffness. The change in trunk position at IC is therefore important.

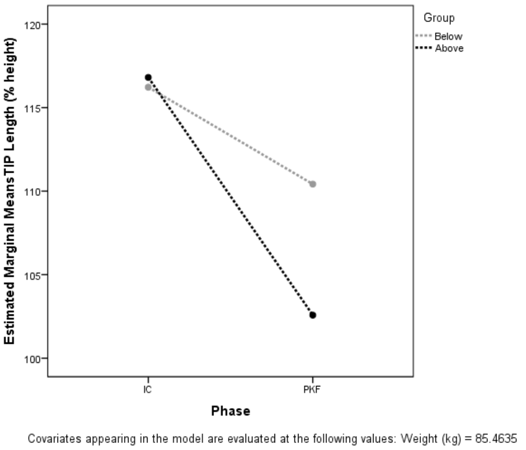
Table 55: Sub classification of landing strategy in the ACLD subjects on the basis of TIP parameters. There are significant differences in hop distance, those with a stiff strategy hopped less far than those with a healthy strategy.

parameter		stiff (n=51)		healthy (n=23)		group differences					
		mean	SD	mean	SD	t	sig.	mean diff	SE	95% CI lower	95% CI upper
hop distance		.69	.16	.77	.21	2.69	.009	-.12	0.0	0	0
TIP length (%LL)	IC	116	4.8	117	7.3	-.15	.881	0	1.6	-4	3
	PKF	111	6.3	102	7.1	5.02	<.001	8	1.6	5	12
	Ch	6	3.2	14	3.6	-10.2	<.001	-8	.8	10	-7
TIP angle (°)	IC	80	4.6	76	5.1	3.87	<.001	5	1.2	2	7
	PKF	84	5.6	85	7.5	-.08	.933	0	1.6	3	3
	Ch	4	4.8	9	6.2	-3.58	.001	-5	1.3	7	2
knee flexion (°)	IC	28	8.8	28	14.1	.17	.860	1	3.1	-6	7
	PKF	46	9.4	58	12.3	-4.82	<.001	-13	2.6	-18	-7
	Ch	18	11.7	31	12.5	-4.39	<.001	-13	3.0	-19	-7
trunk lean (°)	IC	8	7.0	14	8.1	-3.34	.001	-6	1.8	-10	-3
	PKF	7	10.4	15	11.0	-3.25	.002	-9	2.6	-14	-3
	Ch	-2	6.6	1	8.3	-1.38	.171	-3	1.8	-6	1

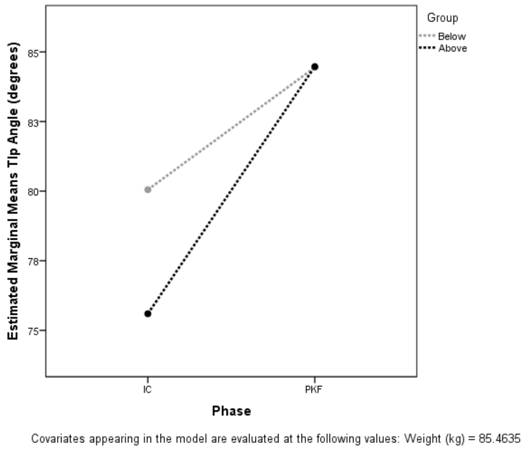
Key: TIP length (% leg length), hop distance normalised to height, IC = initial contact, PKF = peak knee flexion, Ch = change between phases, H = Healthy, ACLD = Anterior Cruciate Ligament Deficient, M = Mean, SE = Standard error of the mean, CI = confidence interval, ES = Effect size.

Figure 31: Interaction plots for Phase (IC and PKF on x axis) and Group (healthy in grey and Stiff in black) for the TIP and kinematic parameters during Hop landing; the different gradients in the TIP parameters clearly show the different strategies, there are differences in knee flexion at PKF and a more dramatic difference in forward trunk lean throughout the landing phase shown by the large separation on the plots.

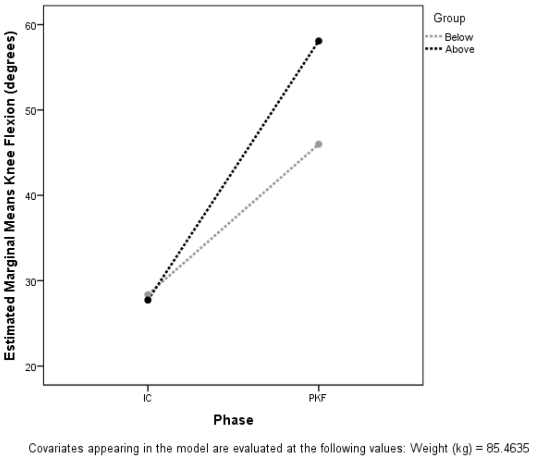
TIP length (% leg length)



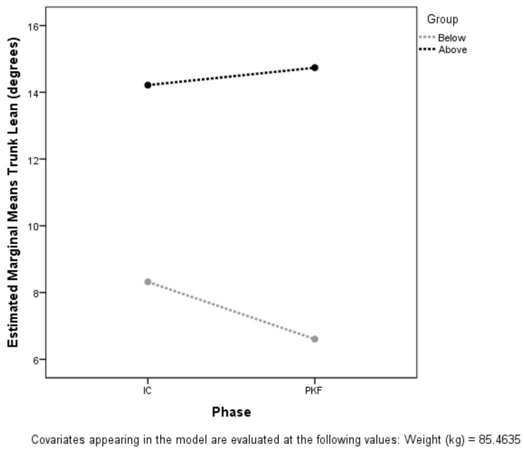
TIP angle (°)



knee flexion (°)



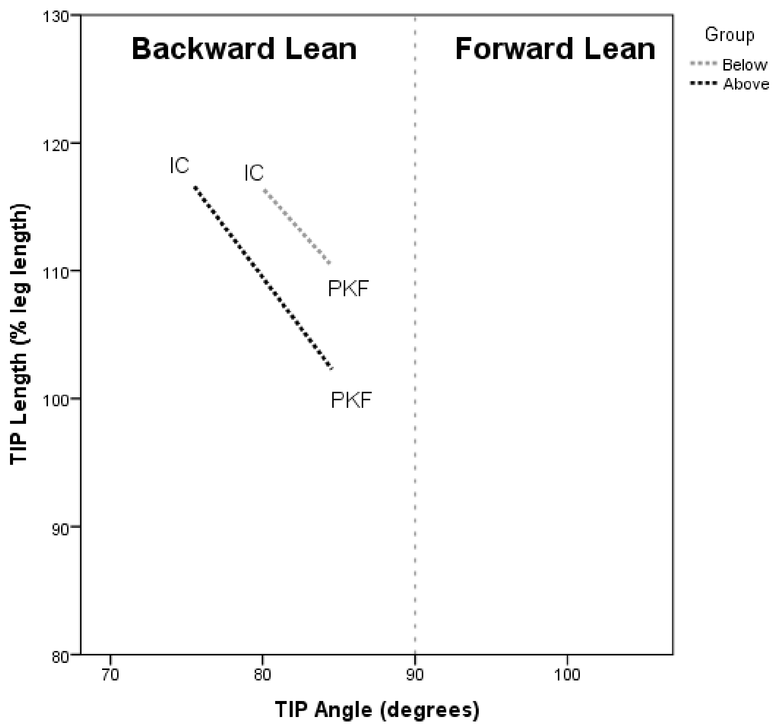
trunk lean (°)



Key: The Interaction terms between group and phase were significant for the TIP parameters and the knee flexion parameter but not the trunk lean parameter. TIP length $F(2,70) = 102.166$ $P < 0.001$, Partial Eta Squared = 0.59), TIP angle $F(2,70) = 12.244$ $P = 0.001$, Partial Eta Squared = 0.15), knee flexion(2,70) =18.457 $P < 0.001$, Partial Eta Squared = 0.21), trunk lean $F(2,70) = 1.585$ $P = 0.212$, Partial Eta Squared = 0.22)

Therefore, in the ACLD group, landing strategy could be sub classified as stiff or healthy on the basis of TIP parameters (Figure 32). However, further investigation of the kinematics indicated that this strategy was not as healthy as suggested by the TIP parameters. These subjects used knee flexion that was greater than other ACLD subjects and similar to healthy. However, they utilised an adaptation in the trunk, leaning further forward at IC and throughout the landing phase that the healthy subjects. This strategy seems to bring TIP parameters within healthy values; however it represents a compensatory strategy, most likely in response to reduced flexion at the knee.

Figure 32: plot of TIP length (y axis) and TIP angle (x axis) demonstrating the identified sub classification of landing strategies in the ACLD subjects; Healthy (black line) and stiff (grey line).



Hierarchy of performance parameters

The average deficits in activity parameters for the injured leg of ACLD subjects in comparison to healthy are summarised in Figure 33. Recovery of each activity against the clinical significance criteria is summarised in Table 56. As hypothesised, there was a hierarchy such that gait deficits are least, squat are intermediate and hop the most affected. The deficits in the non-injured limb are smaller but follow the same hierarchical pattern.

Figure 33: A hierarchical pattern of mean deficits from healthy values was identified in the activity parameters of the ACLD subjects; gait velocity shows the smallest deficit, hop distance the greatest and squat depth is intermediate.

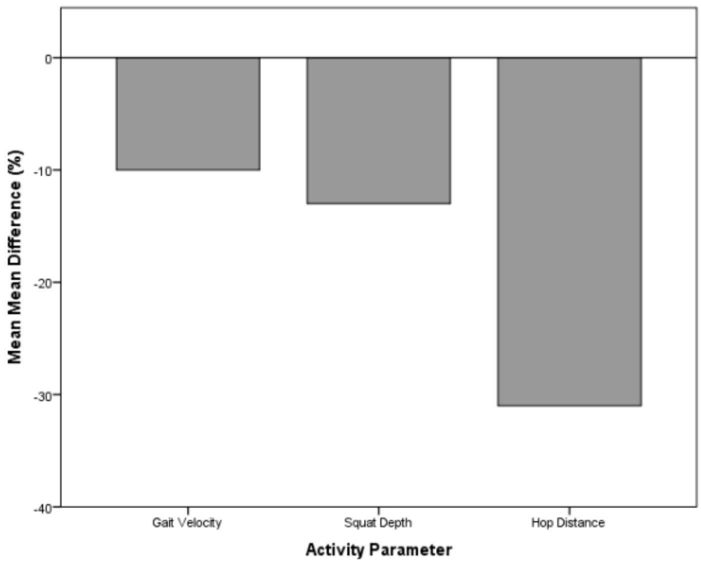


Table 56: Frequency distribution data for recovery to healthy performance in the ACLD subjects defined by the clinical significance criteria.

		recovery		
		failure	**partial**	**full**
gait velocity (m/s)	**criteria**	<1.26		>1.325
	ACLD n	44	8	22
Squat PKF (°)	**criteria**	>105		<97.5
	ACLD n	40	10	24
hop distance (m/height)	**criteria**	<.76		>0.825
	ACLD n	57	7	10

Key: ACLD n = number of ACLD subjects, Failure to recover is > 1 SD below healthy mean, Partial recovery is <1 and >0.5 SD below healthy mean, Full recovery is <0.5 SD below healthy mean.

Summary of results for question one.

Measures of knee function, participation and activities from a group of ACLD subjects prior to surgical reconstruction were explored in comparison to a matched healthy subject group. The functional stability and participation measures confirmed the expectation that the ACLD sample was a group of symptomatically unstable non-copers (with the exception of three adaptors). The null hypothesis for question one was rejected. There are significant deficits in functional performance and knee stability in patients waiting for ACL reconstruction in comparison to normal values. These differences were demonstrated in all three domains of the WHO ICF.

Knee function scores (IKDC SKF) were reduced by an average of 33%, subjects reported moderate levels of pain (VAS) and participation (Tegner) was significantly restricted. The ACLD group was limited in all three activities, with slower walking, fewer squat repetitions with less knee bend, and shorter hop distance with a stiffer landing strategy than the healthy group. The hypothesised hierarchy of activities was supported by the identified deficits such that walking is least effected (10%) followed by squat depth (13%) and hop distance (31%). However, the number of repetitions of single leg squat was the parameter most affected with a mean deficit of 67%. A stiff landing strategy with reduced pendular and telescopic motion has been identified in the ACLD group. This is associated with reduced excursion at the knee and an upright trunk position. There was also a subgroup of ACLD subjects who recovered TIP strategy within healthy values; however this was accompanied by a compensatory strategy utilising increased forward trunk lean throughout the landing phase.

Importantly, these deficits in performance and strategy were found to occur bilaterally in the ACLD group. Although the injured limb showed greater deficits, the non-injured limb was significantly affected in comparison to healthy values. This will have implications for the interpretation of symmetry index values. The healthy subjects are symmetrical in all the parameters, with no significant between limb differences. However the ACLD subjects were significantly asymmetrical. The limb symmetry standards previously recommended in the literature for hop testing were found to be conservative in comparison to those identified by healthy comparison in this group. The bilateral deficits demonstrated here suggest that it is likely that any limb symmetry score will underestimate deficits in comparison to healthy values. Whilst the majority of ACLD subjects had significant deficits there were some subjects who had recovered within healthy values for the activity parameters prior to surgery.

Three themes emerge from these findings:

1. ACLD subjects demonstrated deficits in performance and altered strategy in three activities.
2. Deficits in functional performance and strategy in ACLD subjects were consistent with the hypothesised hierarchy.
3. Deficits in ACLD subjects were bilateral, limiting the utility of symmetry standards.

Question Two

Question: Is functional performance and knee stability improved 1 year following ACLR and rehabilitation?

Functional stability

The distribution of severity of functional knee instability on the Lysholm instability subscale for the subjects prior to (ACLD) and 1 year after (ACLR) surgery is presented in Figure 34 and Table 57. Improvements in functional stability are evident in the population pyramid (Figure 34). At 1 year following ACLR, 46 (62%) subjects reported no instability and 16 (21%) rarely with vigorous activity however 12 (17%) remained troubled with frequent instability occurring with ADL. No subjects reported worsening of instability following ACLR. Inferential statistics are presented in Table 58 and demonstrate that on average, ACLR subjects reported less instability than they did prior to surgery. This difference is statistically significant (P<0.001) and represents a large effect (ES = .74).

Figure 34: Population pyramid showing the distribution of instability on the Lysholm subscale before (ACLD) and 1 year after ACLR (ACLR).

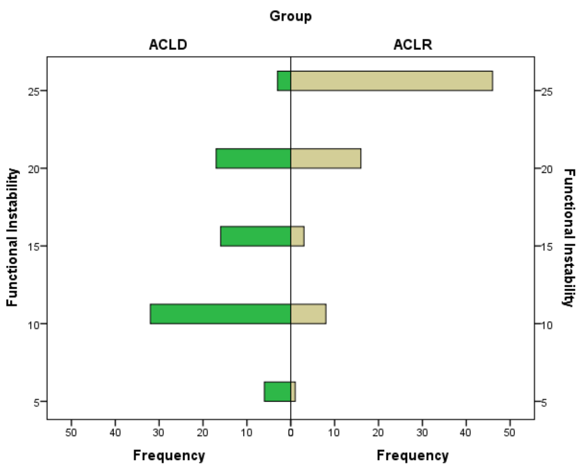


Table 57: Distribution of instability of the Lysholm subscale before (ACLD) and 1 year after ACLR (ACLR). Higher score indicates less instability, 25 represents "no giving way" and 0 "giving way at every step".

Lysholm give way	ACLD		ACLR	
	n	%	n	%
5	6	8	1	1
10	32	43	8	12
15	16	22	3	4
20	17	23	16	21
25	3	4	46	62

Table 58: Differences in functional stability (Lysholm subscale) in the same subjects before (ACLD) and 1 year after ACLR and rehabilitation; there are significant improvements in functional stability 1 year following ACLR.

parameter	group	median	IQR	paired differences			
				statistic	df	sig.	ES
give way	ACLD	20	15	Z = 6.354	74	<.001	0.74
	ACLR	25	5				

Key: ACLD = Anterior Cruciate Ligament Deficient subjects, ACLR = Anterior Cruciate Ligament reconstructed subjects, IQR = interquartile range, df = degrees of freedom, ES = effect size.

Participation

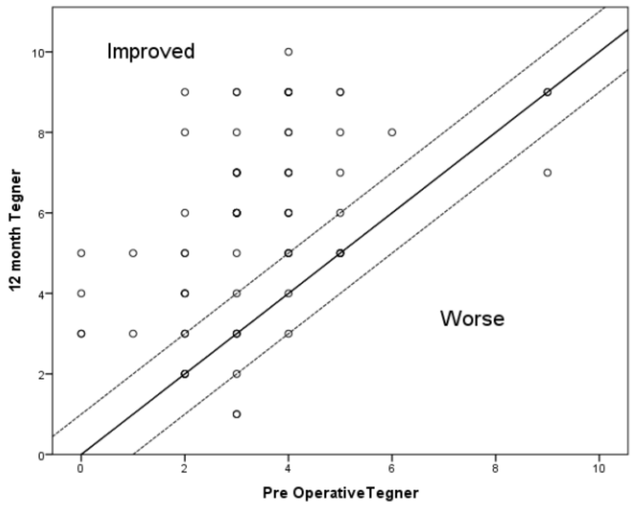
Descriptive and inferential statistics are presented in Table 59. The median Tegner score has risen to 6 (IQR = 3), the change relative to pre-operative (ACLD) is presented in the scatter plot in Figure 35; those above the diagonal line have improved. On average, subjects 1 year following ACLR have greater Tegner scores than they did prior to surgery; these differences are significant with large effect size (ES = 0.54). The SEM identified in this sample (Letchford et al., 2015) was 0.63, therefore 1 point change was considered as the reliable change index (RCI). On this criterion 5 subjects have a lower Tegner score at 1 year following ACLR than they reported before surgery.

Table 59: Differences in participation (Tegner) in same subjects before (ACLD) and 1 year after ACLR and rehabilitation; there are significant improvements in participation 1 year following ACLR.

parameter	group	median	IQR	paired differences			
				statistic	df	sig.	ES
Tegner (0-10)	ACLD	3	2	Z = -6.535	148	<.001	.54
	ACLR	6	3				

Key: ACLD = Anterior Cruciate Ligament Deficient subjects, ACLR = Anterior Cruciate Ligament reconstructed subjects, IQR = interquartile range, df = degrees of freedom, ES = effect size.

Figure 35: Scatter plot for clinical significance of changes in Participation. Tegner scores are plotted before (x axis) and 1 year after (y axis) ACLR. The solid diagonal line represents no change; the dashed lines represent measurable change and are set at the SEM of the Tegner scale.



Knee Function

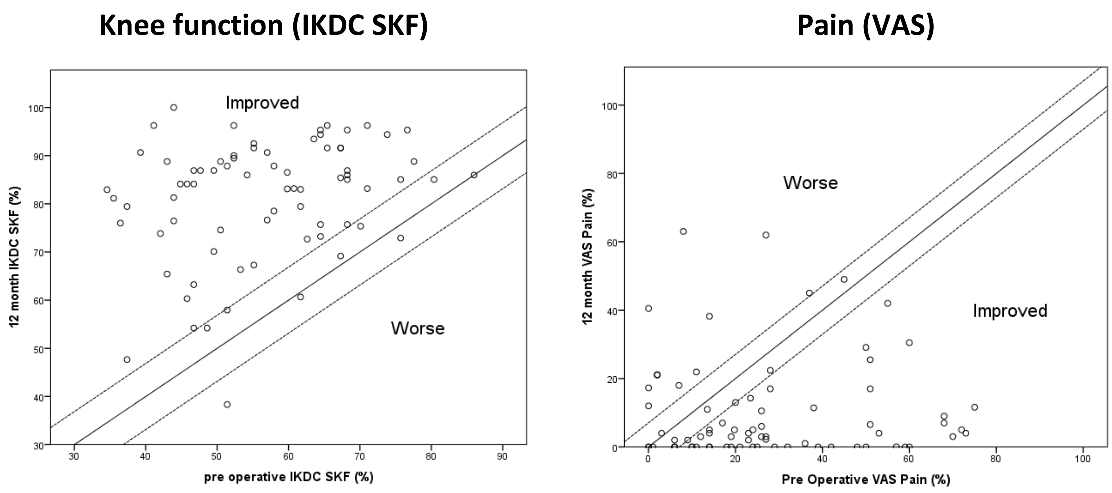
Descriptive and inferential statistics for all the PROMS data is displayed in Table 60. There were average improvements in knee function following ACLR on both the Lysholm and IKDC SKF. These differences were statistically significant and represented large effects (ES>0.5). Both scores demonstrated similar mean increases (Lysholm 22% and IKDC 24%) in self-reported knee function. Scatter plots showing the changes on the IKDC SKF is displayed in Figure 36. When classified on the basis of change with a RCI of 6.861, 1 subject is classified as worse, 8 unchanged and 65 improved. Self-reported knee function was statistically and clinically significantly improved 1 year following ACLR. There were average reductions in levels of pain severity 1 year following ACLR. This difference was statistically significant and represents a large effect (ES = 0.52). The mean difference of 16mm represents a mean 57% reduction in pain. A scatter plot showing the pre-post comparison is displayed in Figure 36. The RCI was 7.06 and when classified on this basis there were 10 subjects who were in more pain, 10 unchanged and 54 in less pain than prior to ACLR. Pain severity was statistically and clinically significantly reduced 1 year following ACLR. Therefore, both self-reported knee function and pain showed statistically and clinically significant improvements 1 year following ACLR.

Table 60: Differences in knee function (IKDC SKF and Lysholm) and pain (VAS) in same subjects before (ACLD) and 1 year after ACLR and rehabilitation; there are significant improvements for all parameters.

parameter	group	mean	SE	paired differences							
				statistic	df	sig.	mean diff	SE	ES	95% CI	
										lower	upper
IKDC SKF (%)	ACLD	61	1.5	t = 8.849	98	<.001	-24	3.5	.67	-31	-17
	ACLR	84	3.4								
Lysholm (0-100)	ACLD	57	1.4	t = 6.422	16	<.001	-22	4.1	.85	-31	-13
	ACLR	79	3.2								
VAS Pain (0-100)	ACLD	28	2.6	t = 5.721	87	<.001	16	3.6	.52	9	24
	ACLR	12	2.9								

Key: ACLD = Anterior Cruciate Deficient subjects, H = Healthy Subjects, M = mean, SE = Standard error of the mean, df = degrees of freedom, ES = effect size, CI = confidence interval.

Figure 36: Scatter plots showing the clinical significance of changes in Knee function (IKDC SKF) and pain (VAS) 1 year after ACLR and rehabilitation. Solid line represents no change; dashed lines represent the limits of the reliable change index, change greater than the RCI indicates a clinically significant change.



Activity

Gait

Descriptive and inferential statistics are displayed in Table 61 and 62. On average, 1 year following ACLR subjects walked more quickly than they did before surgery. This difference was statistically significant; the mean difference of .08 m/s represents an increase of 7% and a moderate effect size (r= .43). Gait velocity was again a significant covariate for all other gait parameters and when included in the analysis there were no differences in the other gait parameters between the groups. A scatter plot showing the pre-post comparison is displayed in Figure 37. The reliable change index (RCI) was 0.058 and when classified on this basis there were 14 subjects who walked slower, 18 unchanged and 42 who walked faster at ACLR than they did before surgery. Gait velocity was therefore statistically and clinically significantly increased 1 year following ACLR.

Table 61: Exploration of gait velocity as a covariate for differences in the gait strategy parameters in same subjects before (ACLD) and 1 year after ACLR and rehabilitation; gait velocity was a significant covariate for the gait strategy parameters.

parameter	group	mean	SD	statistic	sig.	ES
cadence	**ACLD**	106	8.34	F = 206.358	<.001	.59
	ACLR	109	7.68			
SLI	**ACLD**	0.68	0.08	F = 318.979	<.001	.69
	ACLR	0.72	0.07			
SLN	**ACLD**	0.69	0.08	F = 372.740	<.001	.72
	ACLR	0.72	0.07			
symm	**ACLD**	99	7.31	F = 0.125	.724	.00
	ACLR	100	7.00			

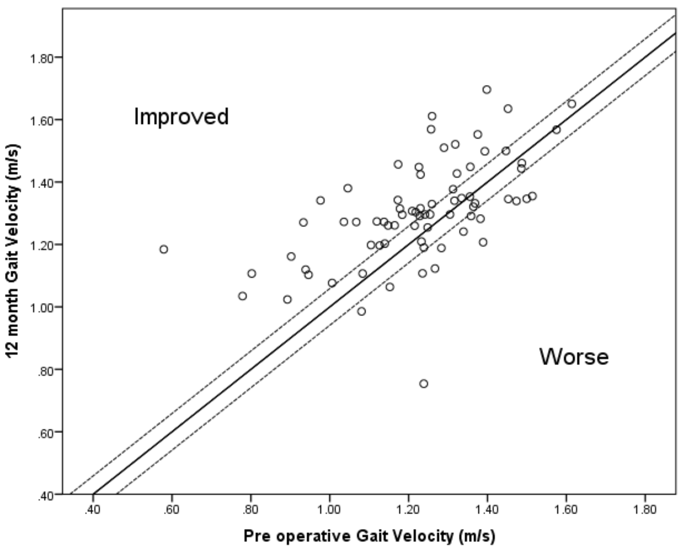
Key: cadence (steps per minute), SLI = step length injured limb (m), SLN = step length non-injured limb (m), symm = step length symmetry (%), ES = effect size.

Table 62: Differences in Gait parameters between same subjects before (ACLD) and 1 year after ACLR and rehabilitation; there were significant differences only for gait velocity (highlighted in greyscale).

parameter	group	mean	SE	statistic	sig.	ES	mean diff	SE	95% CI	
									lower	upper
velocity	ACLD	1.22	.02	t = -4.128	<.001	.43	-.08	.03	-.12	.04
	ACLR	1.30	.02							
cadence	ACLD	108	1	F = 0.000	.993	.00	0	1	-2	2
	ACLR	108	1							
SLI	ACLD	0.70	.01	F = 0.190	.663	.00	0	.01	-.02	.01
	ACLR	0.70	.01							
SLN	ACLD	0.71	.00	F = 0.079	.779	.00	0	.01	-.01	.02
	ACLR	0.70	.00							
symm	ACLD	99	7	t = -1.502	.137	.17	-1	1	-2	0
	ACLR	100	7							

Key: velocity (m/s), cadence (steps / minute), SLI = step length injured (m), SLN = step length non-injured (m), symm = step length symmetry (% uninjured leg), M = mean, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

Figure 37: Scatter plot showing clinical significance of changes in gait velocity 1 year after ACLR and rehabilitation. Solid line represents no change; dashed lines represent the limits of the reliable change index, change greater than the RCI indicates a clinically significant change.



Single Leg Squat

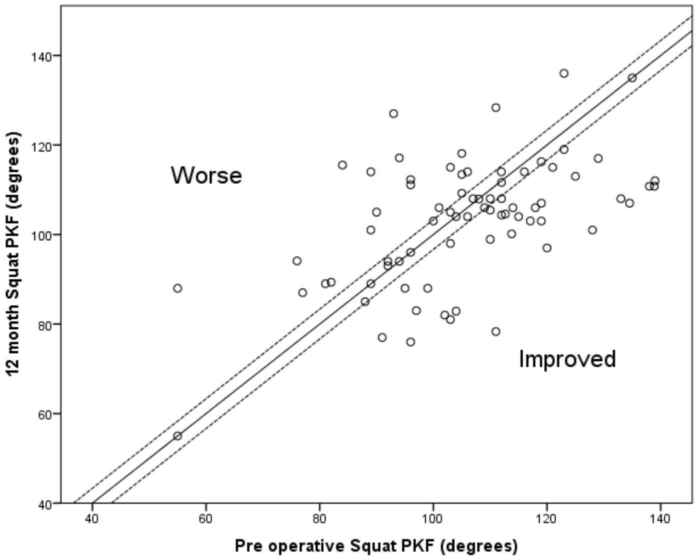
Descriptive and inferential statistics are presented in Table 63. On average, 1 year following ACLR, subjects performed more squat repetitions on the injured leg than they did before surgery. This difference was statistically significant, the mean difference of 7 repetitions (95% CI = 4 to 9) represents a mean increase of 100%. This was also the case on the non-injured limb where there was a mean increase of 6 reps (95%CI = 4 to 9). There were 61 subjects who stopped due to a loss of balance and 13 who elected to stop for other reasons. There was again no difference between these groups for the number of repetitions ($t(72) = 0.527$, $P = 0.569$), squat depth ($t(72) = -0.426$, $P = 0.672$), pain ($t(72) = -0.937$, $P = 0.352$) or Knee Function on IKDC SKF ($t(72) = -0.848$, $P = 0.399$). On average, 1 year following ACLR, subjects squatted with greater peak knee flexion for the injured leg than they did when ACLD. However, this difference was not statistically significant; the mean difference was 2 degrees (95% CI = 1.6 to -1.4). For the non-injured leg there was an average reduction in squat depth following ACLR, This was significant; the mean difference of 4 degrees (95% CI = 7 to 1) represents a small effect (ES = 0.25) and a 4% average decrease. A scatter plot showing changes on the basis of clinical significance is displayed in Figure 38 When classified on the basis of change with a reliable change index (RCI) of 3.3 degrees, there were 21 subjects who squatted less deep, 20 unchanged and 33 who squatted more deeply 1 year following ACLR.

Table 63: Differences in squat parameters between same subjects before (ACLD) and 1 year after ACLR and rehabilitation; there were significant increases in squat repetitions on both legs and significant reduction in squat depth on the non-injured leg.

Squat param	leg	group	mean	SE	statistic	sig.	ES	mean diff	SE	95% CI	
										lower	upper
reps	inj	ACLD	7	.67	t = -5.849	<.001	.56	-7	1.4	-9	-4
		ACLR	14	1.29							
	non	ACLD	10	.94	t = -5.253	<.001	.52	-6	1.4	-9	-4
		ACLR	16	1.29							
depth	inj	ACLD	106	1.98	t = 1.413	.162	.16	2	1.7	-1	5
		ACLR	103	1.64							
	non	ACLD	97	1.68	t = -2.193	.031	.25	-4	1.7	-7	-1
		ACLR	100	1.48							

Key: reps = squat repetitions (number), depth = peak knee flexion (°), inj = Injured leg, non = non-injured leg, SE = Standard error of the mean, ES = effect size, CI = Confidence interval.

Figure 38: Scatter plot showing clinical significance of changes in squat depth 1 year after ACLR and rehabilitation; solid line represents no change; dashed lines represent the limits of the reliable change index, change greater than the RCI indicates a clinically significant improvement. Smaller PKF indicates better performance, bottom right is improved.



Squat symmetry: between limb differences in ACLR

Between limb differences are displayed in Table 64. There was no significant difference in the number of squat repetitions performed on the injured and non-injured legs in the ACLR group; however there was a significant difference in the squat depth; with a mean difference of 8 degrees.

Table 64: Differences in squat repetitions and squat depth between limbs in subjects 1 year following ACLR and rehabilitation; there were no significant differences in squat repetitions and significantly less squat depth on the injured leg.

squat parameter	leg	mean	SE	statistic	sig.	ES	mean diff	95% CI	
								lower	upper
repetitions	**inj**	13	1.22	t = -0.878	.384	.10	-1	-3	1
	non	14	1.09						
depth	**inj**	104	1.8	t = 4.936	.000	.49	8	5	11
	non	96	1.5						

Key: repetitions (number), depth = peak knee flexion (°), inj = injured leg, non = non-injured leg, SE = Standard error of the mean, ES = effect size, CI = confidence interval.

Therefore, squat repetitions were statistically significantly improved 1 year following ACLR, however squat depth was not. Over half the subjects were unchanged or squatted less deeply 1 year following ACLR. Interestingly, squat depth on the non-injured limb demonstrated small but statistically significant reductions at 1 year following ACLR. Even with this reduced performance on the non-injured limb, subjects remained significantly asymmetrical in squat performance. It would appear that squat depth is not significantly improved with current rehabilitation practice.

Hop for Distance

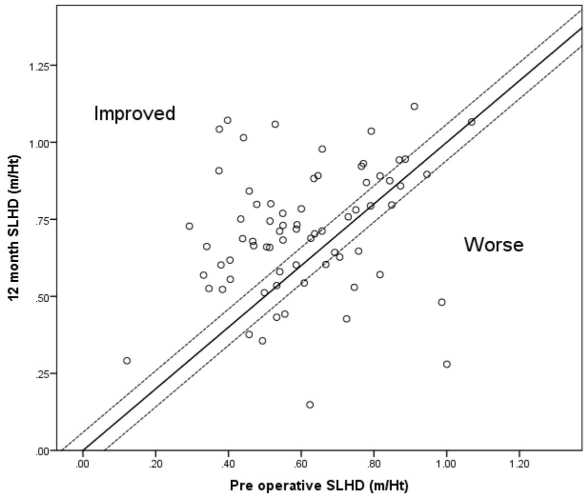
Descriptive and inferential statistics are presented in Table 65. On average, subjects hopped further 1 year following ACLR than they did when ACLD, the difference was statistically significant on both legs. The mean difference represents an improvement in performance of 20% for the injured leg and 14% on the uninjured leg. A scatter plot showing changes on the basis of clinical significance is displayed in Figure 39. When classified on the basis of change with a RCI of 0.059 m/ht, there were 14 subjects who hop less far, 14 unchanged and 46 increased hop distance between ACLD and ACLR.

Table 65: Differences in hop distance between the same subjects before (ACLD) and 1 year after ACLR and rehabilitation; ACLR subjects hop further on both the injured and non-injured limbs.

leg	group	mean	SE	statistic	sig.	ES	mean diff	SE	95% CI	
									lower	upper
inj	ACLD	.61	.02	t = -4.017	<.001	.32	.12	.03	-.18	-.06
	ACLR	.73	.03							
non	ACLD	.79	.02	t = -3.570	<.001	.29	.07	.02	-.11	-.03
	ACLR	.87	.02							

Key: Hop distance is normalised to height, inj = Injured leg, non = non-injured leg, ACLD = Anterior Cruciate Deficient subjects, ACLR = Anterior Cruciate reconstructed subjects, SE = Standard error of the mean, mean diff = mean difference, CI = confidence interval, ES = Effect size.

Figure 39: Scatter plot showing the clinical significance of changes in hop distance 1 year after ACLR and rehabilitation; solid line represents no change; dashed lines represent the limits of the reliable change index, change greater than the RCI indicates a clinically significant change, above the line is improved.



Hop Symmetry

Distribution of hop symmetry data and the frequency of passing each of the previously proposed standards is displayed in Table 66. There was an increase in hop LSI in the ACLR subjects compared to ACLD, however this is not statistically significant (t(73) = 1.054, P = 0.295, r = 0.12). There were fewer people who failed the 85% criteria, and more who passed the higher criteria. A scatter plot showing changes on the basis of clinical significance is displayed in Figure 40. When classified on the basis of change with a RCI of 8%, there were 17 (23%) subjects who were more asymmetrical, 26 (35%) unchanged and 31 (42%) with improved symmetry.

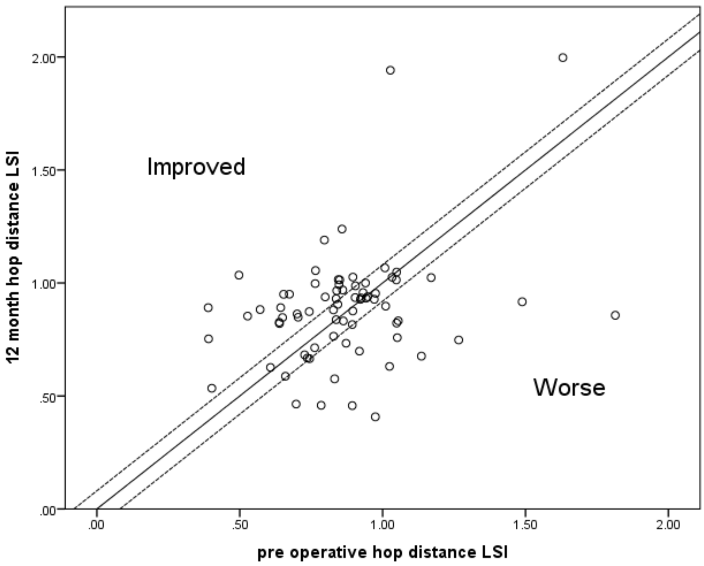
Therefore, Hop performance was statistically and clinically significantly improved 1 year following ACLR. Improvements were seen for both limbs, although greater change was demonstrated in the injured limb.

Table 66: Distribution of hop distance limb symmetry index (LSI) in same subjects before (ACLD) and 1 year after ACLR, and the frequency distribution when each of the published Limb Symmetry (LSI) criteria are applied; ACLR subjects are more symmetrical and a greater number pass the more rigorous LSI criteria.

	ACLD		ACLR	
Mean (SD)	**87% (24)**		**91% (32)**	
LSI	**n**	**%**	**n**	**%**
<85%	**35**	**47**	**27**	**36**
85% - 90%	**9**	**12**	**11**	**15**
90%- 95%	**10**	**14**	**11**	**15**
95%- 100%	**20**	**27**	**25**	**34**

Key: n = number of subjects; SD = Standard deviation; LSI = limb symmetry index

Figure 40: Scatter plot showing clinical significance of changes in hop Limb symmetry index 1 year after ACLR and rehabilitation. Solid line represents no change; dashed lines represent the limits of the reliable change index, change greater than the RCI indicates a clinically significant improvement. Above the line is improved.



Hop Strategy: 2D TIP

Descriptive and inferential statistics are presented in Table 67 and 68. Hop distance was a significant covariate for TIP length at peak knee flexion, TIP length change, TIP angle at initial contact and TIP angle change and was therefore included in these analyses. The only parameter with significant difference between groups was the TIP length change parameter, with a mean increase of 3% leg length. This appears to be due to a trend towards reduction in TIP length at peak knee flexion, rather than changes at initial contact. The TIP strategy was therefore more telescopic. There was a trend for the TIP angle change to become greater; this appears to be due to a trend towards a reduced TIP angle at IC, rather than changes at PKF. This suggests that the strategy was also becoming increasingly pendular.

Table 67: Exploration of hop distance as a covariate for differences in the telescopic inverted pendulum (TIP) strategy parameters in same subjects before (ACLD) and 1 year after ACLR and rehabilitation; hop distance was a significant covariate for four of the strategy parameters (highlighted in greyscale).

<table>
<tr><th colspan="2">parameter</th><th>group</th><th>mean</th><th>SD</th><th>statistic</th><th>sig.</th><th>ES</th></tr>
<tr><td rowspan="6">TIP length (%LL)</td><td rowspan="2">IC</td><td>ACLD</td><td>116</td><td>6</td><td rowspan="2">F = 2.114</td><td rowspan="2">.148</td><td rowspan="2">.01</td></tr>
<tr><td>ACLR</td><td>116</td><td>6</td></tr>
<tr><td rowspan="2">PKF</td><td>ACLD</td><td>108</td><td>8</td><td rowspan="2">F = 41.216</td><td rowspan="2"><.001</td><td rowspan="2">.22</td></tr>
<tr><td>ACLR</td><td>102</td><td>15</td></tr>
<tr><td rowspan="2">Ch</td><td>ACLD</td><td>9</td><td>5</td><td rowspan="2">F = 38.411</td><td rowspan="2"><.001</td><td rowspan="2">.21</td></tr>
<tr><td>ACLR</td><td>15</td><td>14</td></tr>
<tr><td rowspan="6">TIP angle (°)</td><td rowspan="2">IC</td><td>ACLD</td><td>79</td><td>5</td><td rowspan="2">F = 403.693</td><td rowspan="2"><.001</td><td rowspan="2">.74</td></tr>
<tr><td>ACLR</td><td>75</td><td>6</td></tr>
<tr><td rowspan="2">PKF</td><td>ACLD</td><td>84</td><td>6</td><td rowspan="2">F = 1.520</td><td rowspan="2">.220</td><td rowspan="2">.01</td></tr>
<tr><td>ACLR</td><td>85</td><td>7</td></tr>
<tr><td rowspan="2">Ch</td><td>ACLD</td><td>6</td><td>6</td><td rowspan="2">F = 49.766</td><td rowspan="2"><.001</td><td rowspan="2">.26</td></tr>
<tr><td>ACLR</td><td>10</td><td>9</td></tr>
</table>

Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Change = change between phases, ACLD = Anterior Cruciate Ligament Deficient, ACLR = Anterior Cruciate Ligament reconstructed, SD = Standard deviation, ES = Effect size.

Table 68: Differences in Telescopic Inverted Pendulum (TIP) parameters before (ACLD) and 1 year after ACLR and rehabilitation; TIP length change was significantly increased.

Parameter		group	mean	SE	statistic	sig.	ES	mean diff	SE	95% CI	
										lower	upper
TIP length (%LL)	IC	ACLD	116	0.7	t = 0.310	.757	.03	0	0.9	-2	2
		ACLR	116	0.7							
	PKF	ACLD	106	1.2	F = 3.165	.090	.02	3	1.8	0	7
		ACLR	103	1.2							
	Ch	ACLD	10	1.1	F = 4.115	.050	.03	-3	1.6	-6	0
		ACLR	13	1.1							
TIP angle (°)	IC	ACLD	77	0.3	F = 2.974	.068	.02	1	0.4	0	2
		ACLR	76	0.3							
	PKF	ACLD	84	0.7	t = -0.755	.472	.01	-1	1.1	-3	1
		ACLR	85	0.7							
	Ch	ACLD	7	0.8	F = 3.187	.078	.02	-2	1.1	-4	0
		ACLR	9	0.8							

Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Ch = change between phases, ACLD = Anterior Cruciate Ligament Deficient, ACLR = Anterior Cruciate Ligament Reconstructed, SD = Standard deviation, ES = Effect size for ANCOVA (F) is partial eta and for t tests (t) is r. Bootstrap statistics are presented for TIP L PKF, TIP A IC, TIP A PKF, TIP A Change.

Hop strategy: Kinematics

Descriptive and inferential statistics are presented in Table 69 and 70. Hop distance was a significant covariate for all kinematic parameters and was therefore included as a covariate in all analyses. On average, the knee was less flexed at IC and more flexed at PKF although only at IC is this difference statistically significant. There was a statistically significant increase in the change of knee angle, with ACLR using 7 degrees greater knee bend before PKF than ACLD. On average, the ACLR subjects had increased trunk lean at both IC and PKF although this was statistically significant only at PKF. There was a statistically significant increase in the change in trunk lean, with ACLR subjects increasing the amount of trunk motion by 5 degrees. ACLR subjects therefore adopt a strategy that uses more excursion at both the knee and trunk. This is a less stiff landing strategy, which accounts for the increase in both TIP variables that has been described above.

Therefore, landing strategy showed significant changes in the injured limb of ACLR subjects. The landing was less stiff with increases in both telescopic and pendular components of the COG motion, which are accounted for by increasing excursion in both knee flexion and trunk lean.

Table 69: Exploration of hop distance as a covariate for differences in kinematic parameters during hop landing in same subjects before (ACLD) and 1 year after ACLR and rehabilitation; hop distance was a significant covariate for all strategy parameters.

TIP parameter	phase	group	mean	SD	statistic	sig.	ES
knee flexion (°)	IC	ACLD	28	11	F = 15.124	<.001	.09
		ACLR	25	10			
	PKF	ACLD	50	12	F = 43.799	<.001	.23
		ACLR	58	26			
	Change	ACLD	22	13	F = 18.664	<.001	.11
		ACLR	33	24			
trunk lean (°)	IC	ACLD	10	8	F = 9.742	.002	.06
		ACLR	16	17			
	PKF	ACLD	9	11	F = 20.623	<.001	.13
		ACLR	22	28			
	Change	ACLD	0	7	F = 26.507	<.001	.15
		ACLR	6	12			

Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, ACLD = Anterior Cruciate Ligament Deficient, ACLR = Anterior Cruciate Ligament reconstructed, SD = Standard deviation, ES = Effect size.

Table 70: Differences in Kinematic variables during Hop landing in the same subjects before (ACLD) and 1 year after ACLR and rehabilitation; there are significant increases in knee flexion and trunk lean excursion.

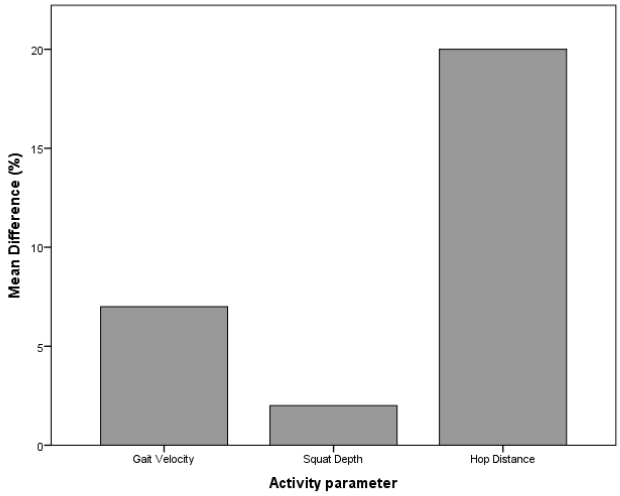
TIP param	phase	group	mean	SE	statistic	ES	mean diff	SE	sig.	95%CI	
										lower	upper
knee flexion (°)	IC	ACLD	29	1.2	F = 9.226	.06	5	1.7	.003	2	8
		ACLR	24	1.2							
	PKF	ACLD	53	2.1	F = 0.537	.00	-2	3.1	.467	-9	4
		ACLR	55	2.1							
	Change	ACLD	24	2.2	F= 5.382	.04	-7	3.0	.021	-14	-2
		ACLR	31	2.2							
trunk lean (°)	IC	ACLD	11	1.6	F = 2.711	.02	-4	2.0	.078	-8	0
		ACLR	15	1.6							
	PKF	ACLD	11	2.4	F = 6.659	.04	-9	3.3	.011	-16	-2
		ACLR	20	2.4							
	Change	ACLD	0	1.1	F= 9.507	.06	-5	1.6	.004	-8	-2
		ACLR	5	1.1							

Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, ACLD = Anterior Cruciate Ligament Deficient, ACLR = Anterior Cruciate Ligament reconstructed, SD = Standard deviation, ES = Effect size. Bootstrap statistics are presented for knee PKF, knee Change, trunk IC, trunk PKF and trunk change.

Hierarchy of activity parameters

The mean change in each of the activity parameters is displayed in Figure 41. The hypothesised hierarchy between gait and hop is partially supported, with greater improvement seen in the more complex hop task. Squat depth no longer fits the hierarchy, demonstrating less improvement than gait velocity.

Figure 41: Mean difference in the activity performance parameters in the same subjects before (ACLD) and 1 year after ACLR and rehabilitation; Changes in squat depth do not agree with the hypothesised hierarchy.



Summary of results for question two.

Measures of knee function, participation and activities were explored in the same subjects before and 1 year after ACLR. The null hypothesis for question two was rejected. There were significant improvements in functional performance and knee stability 1 year following ACL reconstruction and rehabilitation. All subjects improved functional stability. There were significant improvements in self-reported knee function on both the Lysholm (22%) and IKDC SKF (24%), an average reduction in pain intensity (VAS) of 57% and significant increases in participation. There were average improvements in most of the activity parameters, with increased gait velocity, squat repetitions and hop distance and a less stiff landing strategy. The clinical significance criteria indicated that there were some subjects who deteriorate in each of the parameters. There was however no change in squat depth. The proposed hierarchy was partially supported by the improvement for gait and hop but not for squat depth. The landing strategy was less stiff with increased telescopic and pendular motion that was accounted for by increasing excursion at both knee flexion and trunk lean. These changes were identified on both the injured and non-injured limbs, although on the whole they were greater on the non-injured leg. The exception is that of squat depth where there was mean reduction in performance on the non-injured limb. Overall, there were mean improvements in all three domains of the ICF one year following ACLR. Subjects had improved functional stability, participation, knee function and performance in two of the three activities tested.

Themes

These findings add to the previously identified themes:

1. ACLD subjects demonstrated deficits in performance and altered strategy in three activities. **There were significant average improvements 1 year following ACLR; however some subjects did not improve on clinical significance analysis.**
2. Deficits in functional performance and strategy in ACLD subjects were consistent with the hypothesised hierarchy. **One year following ACLR, gait and hop performance improved in line with the hierarchy, however squat depth did not.**
3. Deficits in ACLD subjects were bilateral, limiting the utility of symmetry standards. **There were bilateral improvements in hop performance during the first year following ACLR; however squat depth deteriorated further on the non-injured limb.**

Question Three

Question: Do differences in functional performance and knee stability exist between patients 1 year following ACL reconstruction and normal values?

Functional stability

Using the data from the functional stability sub scale of the Lysholm scale previously presented (Table 57) 46 subjects were considered fully recovered (no instability), 16 partially recovered (rarely during severe exertion) and 12 had failed to recover (frequently during exertion or worse) functional knee stability.

Participation

Descriptive and inferential statistics for the Tegner score are presented in Table 71. On average, there were no significant differences between the healthy and ACLR groups at 1 year following surgery. There was however a significant difference between the 12 month scores and the retrospective assessments of pre-injury activity level ($Z(148) = -4.145$, $P < 0.001$) such that pre-injury scores were higher, recovery to pre-injury participation is therefore limited. Application of clinical significance criteria (within the SEM of the Tegner scale and the retrospective assessments) demonstrated that 25 subjects were fully 26 partially and 23 failed to recover participation outcomes.

Table 71: Differences in participation (Tegner) between subjects 1 year after ACLR and rehabilitation, their retrospective assessment of pre-injury participation and matched healthy subjects.

parameter	group	median	IQR	differences			
				statistic	df	sig.	ES
Tegner (0-10)	**Healthy**	6	7 – 10	Z = -0.787	148	.433	.06
	ACLR	6	5 - 8				
	Pre Inj	7	7 – 8.25	Z = -4.145	148	.001	.34
	ACLR	6	5-8				

Key: ACLR = Anterior cruciate ligament reconstructed subjects, Pre Inj = retrospective assessment of pre-injury participation, IQR = interquartile range, df = degrees of freedom, ES = effect size.

Functional Coping

There were 46 subjects who were functionally stable and were therefore potential copers. Twenty of these subjects had recovered pre-injury participation and therefore represented true copers, whilst the remaining 26 failed to recover pre-injury participation (10 were partially recovered and 16 failed to recover) and therefore represent adaptors. The remaining 28 subjects reported some functional instability and were therefore classified as non-copers. Of these, 5 recovered participation to pre-injury levels, 3 were partially recovered and 20 failed to recover participation. With functional coping defined as a stable knee and a return to pre-injury participation, there were 20 true copers, 26 who were functionally stable with modified participation and were therefore adaptors, and 28 who were functionally unstable at their current participation levels and were therefore non-copers. There were 5 subjects who returned to pre-injury participation despite reporting ongoing functional instability (i.e. knee abusers).

Knee Function

Descriptive and inferential statistics for the IKDC SKF are presented in Table 72. On average, ACLR subjects had a lower IKDC SKF score than their age and gender matched normative values; the mean difference was 10%. When the clinical significance criteria were applied to this data, there were 19 (26%) that were classified as fully recovered, 19 (26%) partially recovered and 36 (48%) that failed to recover within healthy values. Pain intensity data is presented in Figure 42. There were 20 subjects who were pain free, the remaining 54 reported pain with a mean severity of 12 (SE = 3) on the VAS. When the criteria of Collins et al. (1997) were applied there were 25 with no pain, 42 with mild pain (<30mm), 5 with moderate pain and 2 subjects with severe pain (>54mm). On the assumption that healthy subjects did not report pain in the knee, pain was considered a significant symptom for the minority in this group of ACLR subjects.

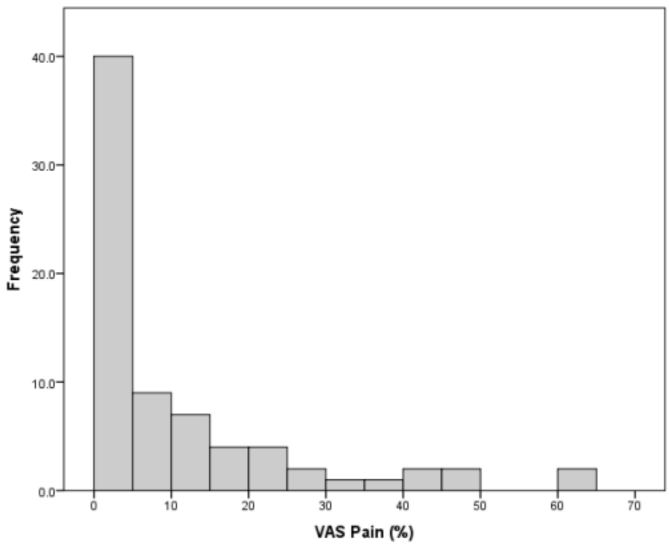
Therefore, mean deficits in knee function compared to age and gender matched healthy values persist 1 year following ACLR, the mean deficit is 10%. Pain remains an issue for the minority of patients

Table 72: Differences in Knee Function (IKDC SKF) between published normative values and the group 1 year following ACLR and rehabilitation: significant deficits in knee function remain in the ACLR group.

parameter	group	mean	SD	differences							
				t	df	sig.	mean diff	SE	ES	95% CI	
										lower	upper
IKDC SKF (%)	Norm	89	.3	5.604	73	<.001	8	1.4	0.55	5	11
	ACLR	81	1.4								

Key: IKDC SKF = International knee documentation committee subjective knee form, Norm = Age and gender matched normative values from Andersson et al. (2006), ACLR = Anterior Cruciate Ligament reconstructed subjects, SD = Standard deviation, M diff = mean difference, SE = standard error of the mean, CI = confidence interval, ES = Effect size.

Figure 42: Frequency distribution of pain scores on the VAS (x axis) for the ACLR group 1 year following surgery and rehabilitation.



Activity

Gait

Descriptive and inferential statistics are displayed in Table 73 and 74. Weight was not a significant covariate for gait velocity and was therefore not included in the analysis. On average, subjects one year following ACLR walked slower than healthy subjects. This difference was statistically significant; the mean difference of 0.08 m/s (95% CI = 0.03 to 0.14) represents a functional deficit of 6%. Gait velocity and weight were significant covariates for all other gait parameters except for symmetry and were therefore included in those analyses. On average, there was no statistically significant difference for gait strategy parameters between the groups. The mean (+/-0.5SD) of the healthy group has been added to the clinical significance scatter plot in Figure 43. On these criteria 32 (43%) subjects were considered fully recovered, 19 partially recovered and 23 failed to recover gait velocity within healthy values. There were 19 subjects who were improved but who had not recovered within healthy values.

Table 73: Exploration of gait velocity and subjects weight as covariates for ACLR and Healthy group differences in gait parameters; gait velocity and weight were significant covariates.

parameter	group	mean	SD	gait velocity			weight		
				statistic	sig.	ES	statistic	sig.	ES
velocity	Healthy	1.39	.13				F = 1.815	.180	.01
	ACLR	1.30	.17						
cadence	Healthy	112	6.6	F = 128.059	<.001	.49	F = 17.438	<.001	.12
	ACLR	109	7.7						
SLI	Healthy	0.73	.06	F = 248.342	<.001	.66	F = 14.907	<.001	.10
	ACLR	0.72	.07						
SLN	Healthy	0.75	.05	F = 280.935	<.001	.68	F = 9.267	.003	.07
	ACLR	0.72	.07						
symm	Healthy	98	4	F = 0.124	.725	.00	F = 0.515	.474	.00
	ACLR	100	7						

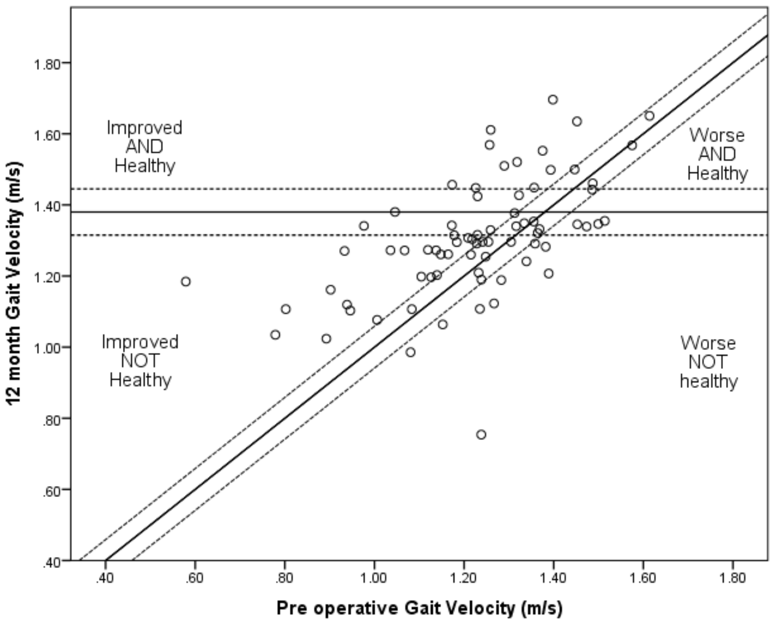
Key: velocity (m/s), cadence (steps/min), SLI = step length injured limb (m), SLN = step length non-injured limb (m), symm = step length symmetry (5), ES = Effect size.

Table 74: Differences in gait parameters between ACLR and Healthy groups; Only gait velocity and step length symmetry demonstrated a significant difference.

parameter	group	mean	SE	differences						
				statistic	sig.	ES	mean diff	SE	95% CI	
									lower	upper
velocity	Healthy	1.39	0.02	t = 3.248	.001	.35	-.09	0.2	.03	.14
	ACLR	1.30	0.02							
cadence	Healthy	111	0.6	F = 0.748	.389	.01	1	1	-2.6	1.0
	ACLR	110	0.7							
SLI	Healthy	0.72	.01	F = 0.017	.895	.00	-.01	.07	-.02	.01
	ACLR	0.72	.01							
SLN	Healthy	0.74	.01	F = 1.386	.241	.01	.01	.01	-.01	.02
	ACLR	0.73	.01							
symm	Healthy	98	0	t = -2.160	.033	0.1	-2	1	-4	0
	ACLR	100	1							

Key: Velocity (m/s), cadence (steps/minute), SLI = step length injured limb (m), SLN = step length non-injured limb (m), Symm = step length symmetry, ACLR = Anterior Cruciate Ligament reconstructed subjects, SE = Standard error of mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

Figure 43: Scatter plot showing the clinical significance of recovery of gait velocity 1 year after ACLR. Horizontal solid line represents the healthy mean, dashed lines represent +/- 0.5 SD, those above the 0.5 SD criterion are considered fully recovered to healthy values.



Key: Horizontal line is the healthy mean +/-0.5SD; Diagonal line represents no change +/- RCI. Those in the top left are improved and within healthy, top right worse but within healthy values, bottom left are improved and not healthy, bottom right worse and not healthy.

Single Leg Squat

Descriptive and inferential statistics are presented in Tables 75 and 76. Weight was a significant covariate for squat depth on both limbs and squat reps on the non-injured limb only and was therefore included in these analyses. On average, subjects 1 year following ACLR performed fewer squats than healthy subjects on both their injured and non-injured leg. This difference was statistically significant only for the injured leg; the mean difference of 7 repetitions (95% CI = 3 to 11) for the injured leg represents a mean functional deficit of 33%. On average, subjects one year following ACLR performed squats with less knee flexion than healthy subjects on both the injured and non-injured leg. These differences were statistically significant; the mean difference of 10 degrees (95% CI = 5 to 16) for the injured leg and 8 for the non-injured leg represents a mean functional deficit of 11% and 9% respectively.

The mean (+/-0.5SD) of the healthy group has been added to the scatter plot in Figure 44. Using the clinical significance criteria, 23 (31%) subjects were considered fully recovered, 14 partially recovered and 37 failed to recover within healthy squat performance. 23 subjects were improved but not within healthy performance.

Table 75: Exploration of subject's weight as a covariate for differences in the squat repetitions and squat depth parameters in subjects 1 year after ACLR and rehabilitation and Healthy; weight was a significant covariate for squat parameters

<table>
<tr><th>squat parameter</th><th>group</th><th>leg</th><th>mean</th><th>SD</th><th>statistic</th><th>sig.</th><th>ES</th></tr>
<tr><td rowspan="4">repetitions</td><td>Healthy</td><td rowspan="2">inj</td><td>21</td><td>12</td><td rowspan="2">F = 0408</td><td rowspan="2">.524</td><td rowspan="2">.00</td></tr>
<tr><td>ACLR</td><td>14</td><td>11</td></tr>
<tr><td>Healthy</td><td rowspan="2">non</td><td>21</td><td>12</td><td rowspan="2">F = 5.688</td><td rowspan="2">.019</td><td rowspan="2">.04</td></tr>
<tr><td>ACLR</td><td>16</td><td>11</td></tr>
<tr><td rowspan="4">depth</td><td>Healthy</td><td rowspan="2">inj</td><td>90</td><td>15</td><td rowspan="2">F = 6.800</td><td rowspan="2">.010</td><td rowspan="2">.05</td></tr>
<tr><td>ACLR</td><td>103</td><td>14</td></tr>
<tr><td>Healthy</td><td rowspan="2">non</td><td>90</td><td>15</td><td rowspan="2">F = 9.737</td><td rowspan="2">.011</td><td rowspan="2">.05</td></tr>
<tr><td>ACLR</td><td>100</td><td>13</td></tr>
</table>

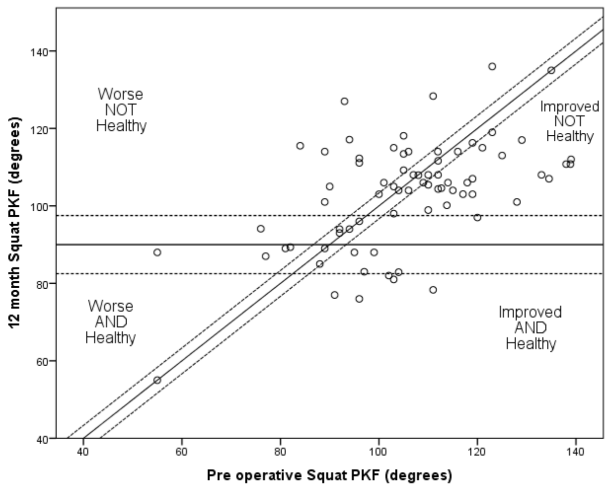
Key: Reps = squat repetitions (number), Depth = peak knee flexion (°), Inj = injured leg, Non = non –injured leg, SD = standard deviation, ES = effect size.

Table 76: Differences in squat repetitions and squat depth parameters between the ACLR and Healthy groups; ACLR subjects perform fewer squat repetitions with less peak knee flexion.

Param	leg	group	mean	SE	statistic	sig.	ES	mean diff	95% CI	
									Lower	Upper
reps	inj	ACLR	14	1.3	t = 3.696	<.001	.31	-7	-11	-3
		Healthy	21	1.6						
	non	ACLR	17	1.4	F = 1.598	.208	.01	-3	-7	2
		Healthy	21	1.6						
depth	inj	ACLR	102	1.7	F = 16.730	<.001	.11	-10	-16	-5
		Healthy	91	1.9						
	non	ACLR	99	1.8	F = 11.025	.001	.08	-8	-13	-3
		Healthy	91	1.9						

Key: Reps = squat repetitions (number), Depth = peak knee flexion (°), inj = injured leg, non = non-injured leg. M = Mean, SE = Standard error of mean, ES = effect size, CI = confidence interval.

Figure 44: Scatter plot showing the clinical significance of recovery of squat depth 1 year following ACLR and rehabilitation. Horizontal solid line represents the healthy mean, dashed lines represent +/- 0.5 SD, those above the 0.5 SD criterion are considered fully recovered to healthy values. Note that reduced knee flexion angle is an improvement; therefore in contrast to gait velocity and hop distance, improvement is a move to the bottom right.



Key: Horizontal line is the healthy mean +/-0.5SD, Diagonal line represents no change +/- RCI. Those in the top left are improved and within healthy, top right worse but healthy, bottom left improved and not healthy, bottom right worse and not healthy.

Hop for Distance

Descriptive and inferential statistics are displayed in Table 77. On average, subjects 1 year following ACLR hopped less far than the healthy subjects on both limbs. However, this difference was statistically significant only for the injured limb; the mean difference represents a functional deficit of 18%. Clinical significance criteria were applied; the mean +/-0.5SD for the healthy group has been added to the clinical significance scatter plot in Figure 45. On these criteria 24 (33%) subjects were considered fully recovered, 9 partially recovered and 41 failed to recover within healthy ranges for hop distance. There were 27 who were improved but not within healthy values.

Table 77: Differences in hop distance between the Healthy and ACLR groups; 1 year following ACLR subjects hop less far than healthy subjects on the injured limb.

leg	group	mean	SE	differences						
				statistic	sig.	ES	mean diff	SE	95% CI	
									lower	upper
inj	Healthy	.89	.02	t = 4.781	<.001	.38	.16	.03	.09	.22
	ACLR	.73	.03							
non	Healthy	.89	.02	t = 0.881	.380	.07	.04	.04	-.05	.12
	ACLR	.85	.04							

Key: Hop distance is normalised to height, Inj = injured limb, Non = non injured limb, ACLR = Anterior Cruciate Ligament Reconstructed, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

Since there are no longer significant differences between the non-injured limb of ACLR and healthy performance, limb symmetry may now be a more appropriate standard to apply. However it will be important to understand when in the recovery process that may be the case. Table 78 shows the group differences in hop distance for the non-injured limb of ACLR and healthy subjects. Significant differences existed at both 3 and 6 months following surgery. The recovery of non-injured limb performance therefore appears to occur on average between 6 and 12 months following surgery. The actual time of recovery will of course vary between individuals.

Figure 45: Scatter plot showing the clinical significance of recovery of hop distance 1 year following ACLR and rehabilitation. Horizontal solid line represents the healthy mean, dashed lines represent +/- 0.5 SD, those above the 0.5 SD criterion are considered fully recovered to healthy values.

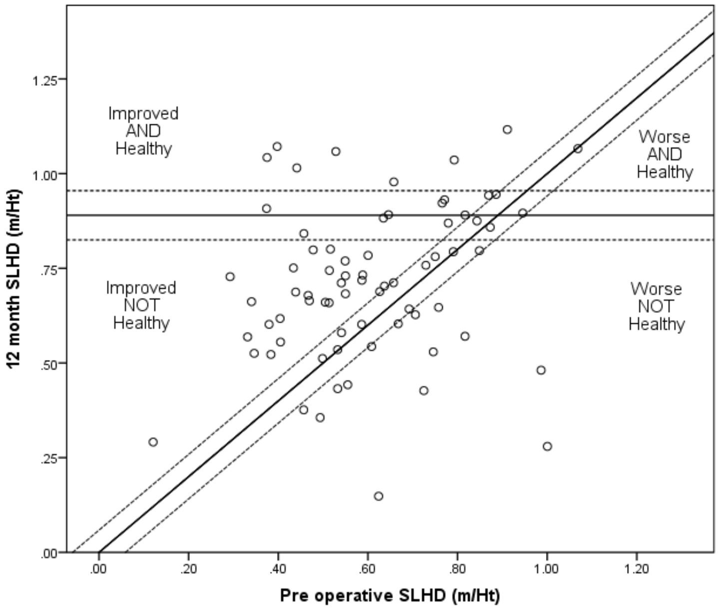


Table 78: Differences in hop distance on the non-injured leg compared to the healthy group at 3 and 6 months following ACLR and rehabilitation; significant differences were demonstrated at both time points suggesting mean recovery of performance on the non-injured limb occurs between 6 and 12 months

time from surgery	group	mean	SE	differences					95% CI	
				statistic	sig.	ES	mean diff	SE	lower	upper
3 months	Healthy	.89	.02	t = 6.616	<.001	.	.18	.03	.13	.23
	ACLR	.71	.02							
6 months	Healthy	.89	.02	t = 4.879	<.001	.	.11	.02	-.07	.16
	ACLR	.77	.02							

Key: Hop distance is normalised to height, ACLR = Anterior Cruciate Ligament Reconstructed, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

Hop Symmetry

Distribution and frequency for passing each of the LSI criteria for hop distance are displayed in Table 79. On average, ACLR subjects have a lower hop LSI than healthy subjects, this difference was statistically significant ($t(133) = 2.577$, $P = 0.012$, $r = 0.22$); the mean difference was 10% (95% CI 2 to 17). This reflects the changes in the non-injured and injured limb identified above. Table 79 clearly shows the variance that is produced by applying each of the LSI criteria to defining recovery in this sample. At the lowest level (85%) there is a 64 % recovery rate, at the highest level (95%) there is a 35% recovery rate. The clinical significance criteria indicate that 19 subjects (26%) were considered fully recovered, 6 (8%) partially recovered and 49 (66%) failed to recover healthy LSI in hop distance.

There are some consistencies in these two approaches; the lowest standard on both these criteria (85% LSI and failure to recover) produced very similar rates of recovery (64 and 66% respectively. This is not so evident at the highest standard (95% LSI and fully recovered) where the clinical significance criteria was harder to achieve (35% and 26% respectively). The clinical significance criteria were clearly a much higher standard to set for recovery than the currently recommended LSI standards.

Table 79: Distribution of hop distance limb symmetry index (LSI) in subjects 1 year after ACLR and healthy group, and the frequency distribution when each of the published LSI criteria are applied; ACLR subjects are more asymmetrical and fewer pass the more rigorous LSI criteria than healthy.

	ACLR		Healthy	
	mean	SD	mean	SD
LSI	0.91	0.32	1.01	0.07
	n	%	n	%
<85%	27	36	0	0
85% - 90%	11	15	3	5
90%- 95%	11	15	6	10
95%- 100%	25	34	52	85

Key: LSI = Limb symmetry index; ACLR = Anterior cruciate ligament reconstructed subjects, SD = Standard deviation, n = number of subjects

Therefore, hop distance was improved but not recovered for the injured limb of subjects 1 year following ACLR, with a mean deficit of 18% from healthy values. Only 24% were considered fully recovered and 41 failed to recover. The non-injured limb performed similarly to the healthy mean, with recovery of this limb occurring on average between 6 and 12 months following surgery. There remains a significant deficit in limb symmetry in comparison to healthy; the use of the currently recommended LSI criteria underestimates deficits when compared to clinical significance criteria on the basis of healthy comparison.

Hop Strategy – 2D TIP

Hop strategy was explored for both the injured and non-injured limb, first using the TIP parameters and then the kinematic parameters. The results will be presented separately for each limb. Descriptive and inferential statistics are displayed in Table 80 and 81. Hop distance was a significant covariate for all TIP parameters except TIP angle at PKF and was therefore included as a covariate in those analyses. On average, ACLR subjects landed with a significantly greater TIP length at IC and used significantly more TIP length change than the healthy subjects to complete the landing. TIP length at PKF is however not significantly different. These differences were reflected in the significant interaction between phase and group ($F(1,132) = 10.501$, $P = 0.002$, Partial Eta Squared = 0.07) and were visually represented by a steeper and longer line in the interaction plot (Figure 46). This indicates a more telescopic strategy in the ACLR subjects. On average, ACLR subjects landed with a greater TIP angle at IC than healthy subjects; the mean difference of 1 degree was however small. There were no significant differences in the TIP angle at PKF, however the difference in change score represented a trend. There was a significant interaction between phase and group ($F(1,132) = 5.674$, $P = 0.019$, Partial Eta Squared = 0.041), which is visually represented by a steeper line that crosses the healthy value, in the interaction plot (Figure 46) . This indicates a more upright posture at initial contact and a more telescopic strategy in the ACLR subjects. The ACLR subjects are therefore landing with a more upright posture at IC and utilising a greater amount of both pendular and telescopic motion before PKF than the healthy subjects.

Table 80: Exploration of hop distance as a covariate for differences in TIP parameters between the ACLR and healthy group; hop distance is a significant covariate for all but the TIP angle at PKF parameter.

TIP parameter	phase	group	mean	SD	statistic	sig.	ES
TIP length (%LL)	IC	Healthy	111	3.1	F = 7.659	.006	.06
		ACLR	116	5.7			
	PKF	Healthy	97	6.5	F = 66.429	<.001	.34
		ACLR	102	14.7			
	Ch	Healthy	13	5.1	F = 49.121	<.001	.27
		ACLR	15	13.9			
TIP angle (°)	IC	Healthy	73	3.0	F = 687.367	<.001	.84
		ACLR	75	5.5			
	PKF	Healthy	84	3.5	F = 2.2.1	.140	.02
		ACLR	85	6.9			
	Ch	Healthy	12	3.6	F = 102.745	<.001	.44
		ACLR	10	9.4			

Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Change = change between phases, ACLR = Anterior Cruciate Ligament Reconstructed, SD = Standard deviation, ES = Effect size.

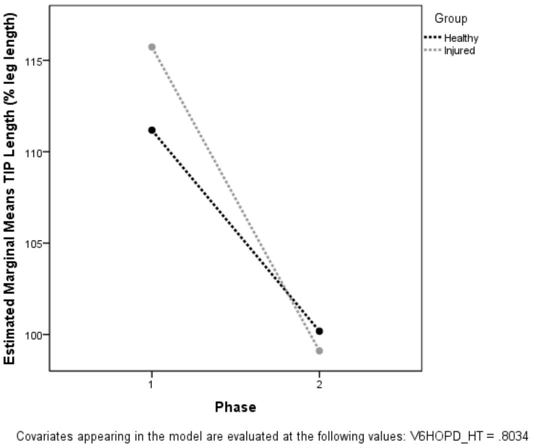
Table 81: Differences in TIP parameters between healthy and ACLR subjects; ACLR subjects continue to land with a greater TIP L at IC, however they now have an increase in change in both TIP length and angle.

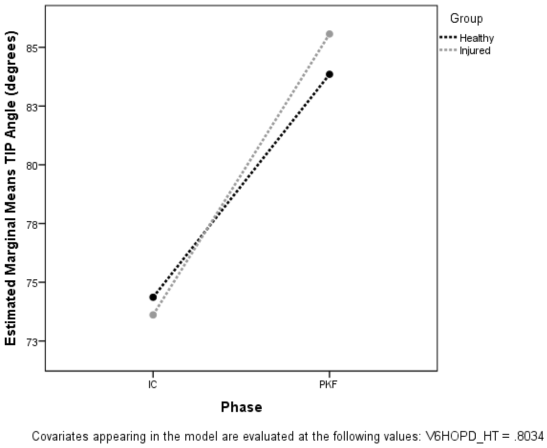
TIP param	phase	group	mean	SE	differences						
					statistic	sig.	ES	m	SE	95% CI	
										lower	upper
TIP length (%LL)	IC	Healthy	111	.6	F = 28.403	.001	.18	5	0.8	-6	-3
		ACLR	116	.6							
	PKF	Healthy	100	1.3	F = 0.362	.632	.00	1	2.2	-3	5
		ACLR	99	1.1							
	Ch	Healthy	11	1.2	F = 10.501	.010	.07	6	1.9	-9	-2
		ACLR	17	1.1							
TIP angle (°)	IC	Healthy	74	0.2	F = 4.841	.030	.04	1	0.3	0	1
		ACLR	74	0.2							
	PKF	Healthy	84	0.4	t = 1.182	.225	.15	1	1.0	-3	1
		ACLR	85	0.8							
	CH	Healthy	9	0.7	F = 5.674	.092	.04	2	1.4	-5	0
		ACLR	12	0.7							

Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Ch = change between phases, H = Healthy, ACLD = Anterior Cruciate Ligament Deficient, M = Mean, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size. **Note:** TIP length at IC and PKF, TIP length Change and TIP angle at PKF and change are bootstrap statistics

Figure 46: Interaction plots for Phase (IC and PKF on x axis) and Group (ACLR in grey and Healthy in black) for the telescopic inverted pendulum (TIP) parameters: the different gradients and crossing lines indicate significant interactions with the ACLR subjects showing a more telescopic and more pendular strategy than the healthy subjects.

TIP length (% leg length) **TIP angle (°)**





Hop Strategy - Kinematics

Kinematic variables were assessed to identify which segments were utilised in this adaptive strategy. Descriptive and inferential statistics are presented in Tables 82 and 83. Hop distance was a significant covariate for all parameters and was therefore included as a covariate in all analyses. On average, ACLR subjects landed with a straighter knee, and used more knee flexion than healthy subjects before PKF. However these differences were not statistically significant. Interaction terms for group and phase were not significant for knee flexion ($F(1,132) = 2.641$, $P = 0.107$, Partial Eta Squared = 0.02), which is represented graphically by the very close association in both length and angle of the plots in Figure 47. On average, ACLR subjects landed with a more forward trunk lean at both IC and PKF and used a greater trunk excursion before PKF than the healthy subjects. These differences were significant at each time point but not in the change score which represented a trend. The interaction terms for group and phase were significant for trunk lean ($F(1,132) = 4.480$, $P = 0.36$, Partial Eta Squared = 0.03) which is demonstrated by the large separation and different steepness of the interaction plot Figure 47. The groups were different at both phases and there was a steeper change in the ACLR group. The ACLR subjects adopted a strategy that uses similar knee flexion to healthy subjects; however trunk lean was increased throughout the landing phase, with greater change between phases. This explains the increase in both length and angle change that was seen in the TIP parameters.

Table 82: Exploration of hop distance as a covariate for differences in the kinematic parameters between ACLR and healthy groups; hop distance is a significant covariate.

parameter	phase	group	mean	SD	statistic	sig.	ES
knee flexion (°)	**IC**	**Healthy**	29	5	F = 28.905	<.001	.18
		ACLR	25	10			
	PKF	**Healthy**	64	11	F = 63.223	<.001	.32
		ACLR	58	26			
	Change	**Healthy**	34	10	F = 31.328	<.001	.19
		ACLR	32	24			
trunk lean (°)	**IC**	**Healthy**	12	7	F = 16.429	<.001	.11
		ACLR	16	17			
	PKF	**Healthy**	19	12	F = 32.004	<.001	.20
		ACLR	22	28			
	Change	**Healthy**	7	8	F = 39.810	<.001	.23
		ACLR	6	12			

Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, ACLR = Anterior Cruciate Ligament Reconstructed, SD = Standard deviation, ES = Effect size.

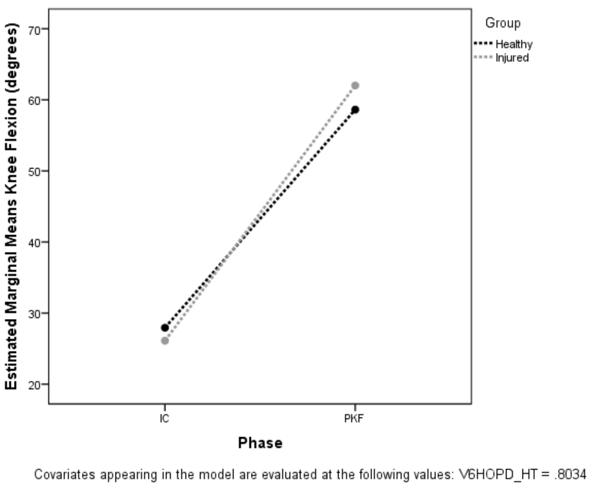
Table 83: Differences in kinematic parameters (knee flexion and trunk lean) during hop landing between ACLR and healthy groups; there were significant differences in trunk lean with greater forward lean in the ACLR subjects (highlighted in greyscale).

param	phase	group	mean	SE	Paired Differences						
					statistic	sig.	ES	m diff	SE	95%CI lower	95%CI upper
knee flexion (°)	IC	Healthy	28	1.0	F = 1.804	.228	.01	2	1.5	-1	5
		ACLR	26	0.9							
	PKF	Healthy	59	2.3	F = 1.144	.373	.01	-3	3.8	-10	4
		ACLR	62	2.0							
	Change	Healthy	31	2.3	F= 2.641	.151	.02	-5	3.5	-12	2
		ACLR	36	2.1							
trunk lean (°)	IC	Healthy	10	1.7	F = 8.767	.031	.06	8	3.1	-13	-1
		ACLR	18	1.6							
	PKF	Healthy	15	2.7	F = 8.678	.029	.06	11	4.6	-20	-2
		ACLR	26	2.4							
	Change	Healthy	5	1.3	F= 4.480	.053	.03	4	1.9	-7	0
		ACLR	8	1.1							

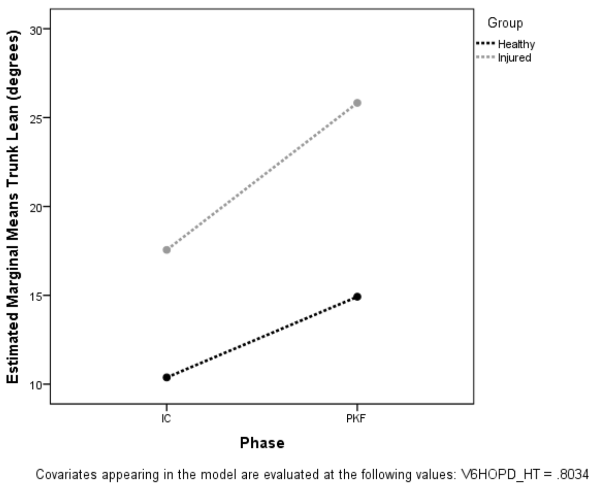
Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, H = Healthy, ACLR = Anterior Cruciate Ligament Reconstructed, M = Mean, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size. **Note:** Bootstrap statistics are presented for all parameters.

Figure 47: Interaction plots for Phase (IC and PKF on x axis) and Group (ACLR in grey and Healthy in black) for the kinematic parameters; the greatest interaction was in the trunk lean where the separated lines indicate altered strategy with increased forward trunk lean throughout the landing .

knee flexion (°)



trunk lean (°)



Hop Strategy on the non-injured limb: 2D TIP

Descriptive and inferential statistics are presented in Tables 84 and 85. Hop distance was not a significant covariate for TIP angle at PKF; however it was for all other parameters and was therefore included as a covariate in those analyses. On average, there were significant differences in TIP length at both IC and PKF such that the ACLR subjects landed with greater TIP length throughout the landing. There was however no significant difference in the change parameter and interaction terms for group and phase were not significant ($F(1,132) = 1.431$, $P = 0.234$, Partial Eta Squared = 0.011). This is seen in the interaction plot (Figure 48) as the two groups show similar gradient, separated at both phases. On average, there were no significant differences in any of the TIP angle variables and interaction terms of group and phase were not significant ($F(1,132) = 0.010$, $P = 0.919$, Partial Eta Squared = 0.000). This is demonstrated by the very close proximity of the two groups with similar gradient and length in the interaction plots (Figure 48). The ACLR subjects had therefore adopted a strategy with greater TIP length throughout the landing phase for their non-injured leg. The strategy was therefore similarly pendular and telescopic, however at a different location on the telescope.

Table 84: Exploration of hop distance as a covariate for differences in TIP Parameters for the non-injured leg between ACLR and healthy subjects; hop distance is a significant covariate.

parameter	phase	group	mean	SD	statistic	sig.	ES
TIP length (%LL)	IC	Healthy	111	3.1	F = 23.261	<.001	.15
		ACLR	115	5.4			
	PKF	Healthy	97	6.5	F = 115.280	<.001	.46
		ACLR	102	10.9			
	Ch	Healthy	13	5.1	F = 226.743	<.001	.63
		ACLR	13	12.7			
TIP angle (°)	IC	Healthy	73	3.0	F = 979.157	<.001	.88
		ACLR	73	7.4			
	PKF	Healthy	84	3.5	F = 0.019	.889	.00
		ACLR	84	5.1			
	Ch	Healthy	12	3.6	F = 258.654	<.001	.66
		ACLR	11	8.6			

Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Change = change between phases, ACLR = Anterior Cruciate Ligament Reconstructed, SD = Standard deviation, ES = Effect size.

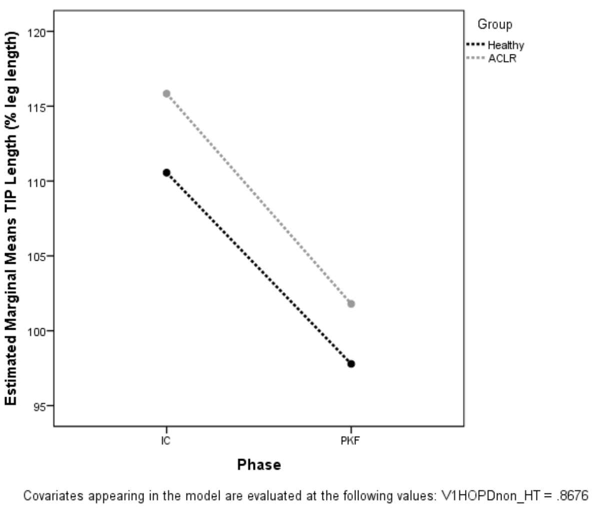
Table 85: Differences in TIP parameters during hop landing on the non-injured limb between ACLR and healthy groups; there were significant differences in TIP length (highlighted in greyscale).

param	phase	group	mean	SE	differences						
					statistic	sig.	ES	M	SE	95% CI	
										lower	upper
TIP length (%LL)	IC	Healthy	110	0.5	F = 53.739	<.001	.12	5	0.7	-7	-4
		ACLR	116	0.5							
	PKF	Healthy	98	0.9	F = 11.870	.001	.08	4	1.2	-6	-2
		ACLR	102	0.8							
	Ch	Healthy	13	0.8	F = 1.431	.234	.01	1	1.1	-3	1
		ACLR	14	0.7							
TIP angle (°)	IC	Healthy	73	0.3	F = 2.389	.125	.02	0	0.4	0	1
		ACLR	72	0.2							
	PKF	Healthy	84	0.4	t = 0.625	.533	.05	0	0.8	-1	2
		ACLR	84	0.6							
	Ch	Healthy	11	0.5	F = 0.010	.919	.00	0	0.7	-1	1
		ACLR	11	0.5							

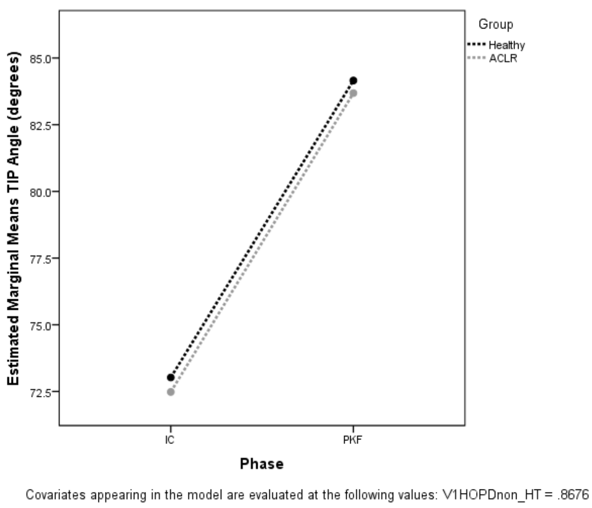
Key: TIP length (% leg length), IC = initial contact, PKF = peak knee flexion, Ch = change between phases, H = Healthy, ACLR = Anterior Cruciate Ligament Reconstructed, M = Mean, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size.

Figure 48: Interaction plots for Phase (IC and PKF on x axis) and Group (ACLR in grey and Healthy in black) for the TIP parameters; there is a significant interaction with greater TIP length throughout in the ACLR subjects demonstrated by the separation of the lines

TIP length (% leg length)



TIP angle (°)



Hop strategy on the non-injured limb: Kinematics

Descriptive and inferential statistics are presented in Tables 86 and 87. Hop distance was not a significant covariate for TIP length at IC; however it was for all other parameters and was therefore included as a covariate in those analyses. On average, there was a significant difference in knee flexion at IC, with the ACLR subjects landing with straighter knee. There was however no significant difference in knee flexion at PKF or in the change variable and the interaction term for phase and group ($F(1,132) = 1.783$, $P = 0.184$, Partial Eta Squared = 0.013) was not significant. The interaction plots in Figure 49 demonstrate this difference in at IC with the similar gradient and length of line to bring the points together at PKF. The healthy limb was therefore straighter at IC but behaved similarly to healthy thereafter. On average, there were no significant differences in trunk lean at either phase, the change variable and the phase by group interaction term was not significant ($F(1,132) = 1.206$, $P = 0.274$, Partial Eta Squared = 0.009). The interaction plots (Figure 49) show the similar gradient and length which are nearly overlapping. Trunk lean was no longer apparent as an adaptive strategy in the ACLR subject's non-injured limb. ACLR subjects were landing with a slightly more extended knee; otherwise there were no significant differences from the healthy landing strategy.

Therefore, the strategy for the injured leg was characterised by greater telescopic and pendular action. The knee moved similarly to healthy, however there was adapted movement occurring at the trunk, with greater amounts of forward lean at initial contact and throughout the landing. The strategy for the non-injured leg was characterised by similar telescopic and pendular action to the healthy group, with a similar increase in the length of the telescope throughout landing. The knee and trunk moved similarly to healthy with a minimally straighter knee at initial contact and a minimally reduced forward trunk lean at peak knee flexion. The slightly longer TIP length throughout the landing was explained by a straighter knee at initial contact and less trunk lean at peak. The average strategy on the injured limb was different from that described in the ACLD subjects, suggesting that recovery was associated with changes in strategy. The strategy variables were therefore explored in relation to recovery within healthy values.

Table 86: Exploration of hop distance as a covariate for differences in kinematic parameters (knee flexion and trunk lean) during hop landing on the non–injured limb between healthy and ACLR subjects; hop distance is a significant covariate.

parameter	phase	group	mean	SD	statistic	sig.	ES
knee flexion (°)	IC	Healthy	29	5	F = 0.057	.811	.00
		ACLR	25	11			
	PKF	Healthy	64	11	F = 163.324	<.001	.55
		ACLR	61	21			
	Change	Healthy	34	10	F = 91.015	<.001	.41
		ACLR	36	26			
trunk lean (°)	IC	Healthy	12	7	F = 74.173	<.001	.36
		ACLR	12	13			
	PKF	Healthy	19	12	F = 90.246	<.001	.41
		ACLR	16	22			
	Change	Healthy	7	8	F = 53.447	<.001	.28
		ACLR	4	11			

Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, ACLR = Anterior Cruciate Ligament Reconstructed, SD = Standard deviation, ES = Effect size.

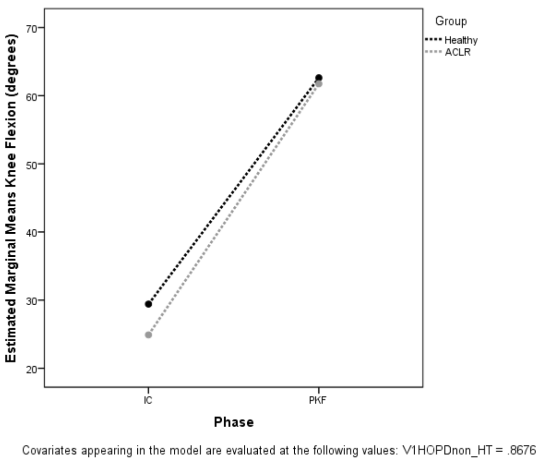
Table 87: Differences in kinematic parameters (knee flexion and trunk lean) during hop landing on the non-injured limb between ACLR and healthy groups; there were significant differences in knee flexion at IC (highlighted in greyscale).

param	phase	group	mean	SE	differences						
					statistic	sig.	ES	m diff	SE	95%CI	
										lower	upper
knee flexion (°)	IC	Healthy	28	1.0	t = 3.416	.001	.28	4	1.3	2	7
		ACLR	26	0.9							
	PKF	Healthy	63	1.5	F = 0.187	.666	.00	1	2.0	-3	5
		ACLR	62	1.4							
	Change	Healthy	33	2.0	F= 1.783	.184	.01	-4	2.7	-9	2
		ACLR	37	1.8							
trunk lean (°)	IC	Healthy	12	1.1	F = 0.035	.853	.00	0	1.5	-3	3
		ACLR	12	1.0							
	PKF	Healthy	18	1.8	F = 0.276	.600	.00	1	2.5	-3	-6
		ACLR	17	1.7							
	Change	Healthy	6	1.1	F= 1.206	.274	.01	2	1.4	-1	4
		ACLR	5	1.0							

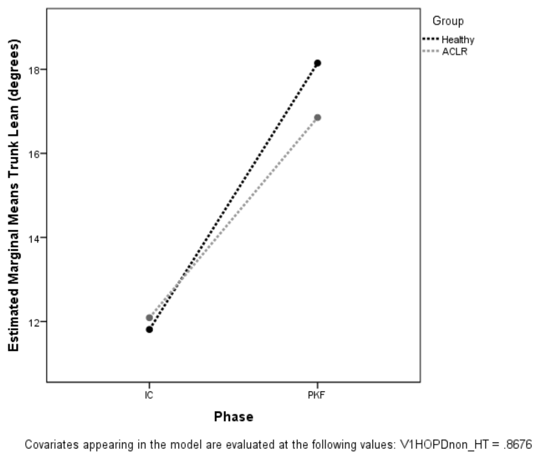
Key: IC = initial contact, PKF = peak knee flexion, Change = change between phases, ACLR = Anterior Cruciate Ligament Reconstructed, M = Mean, SE = Standard error of the mean, M diff = mean difference, CI = confidence interval, ES = Effect size. **Note:** Bootstrap statistics are presented for all parameters

Figure 49: Interaction plots for Phase (IC and PKF on x axis) and Group (ACLR in grey and Healthy in black) for the kinematic parameters during hop landing in ACLD and Healthy on the non-injured leg; Strategies are similar.

knee flexion (°)



trunk lean (°)



Key: IC = Initial contact, PKF = peak knee flexion, Grey = Healthy, Black = ACLR

Recovery of landing strategy

The TIP change parameters consistently showed either significant differences or trends between groups and were therefore used as the primary variables to define landing strategy within the ACLR group. Correlations between strategy and performance are presented in Table 88. There were positive correlations between strategy and performance such that greater changes in both TIP angle and TIP length parameters related to increased hop distance. Subjects were therefore classified on the basis of clinical significance (mean +/-0.5SD) criteria for the TIP parameters, as either below, within or above healthy values. These subgroups are presented in Table 89. A large subgroup of subjects failed to meet the lower criteria (mean – 0.5SD), however a large number also achieved beyond the upper limits of clinical significance (+0.5SD) which suggests the presence of a compensatory mechanism. The group was therefore split on the basis of the clinical significance criteria for each TIP parameter (healthy mean +/-0.5SD). Three subgroups were formed (see Table 90); those that failed to reach healthy values on either TIP variable, those that exceeded healthy values on both TIP change variables and those that were within healthy for one or more TIP variables. There were 40 below healthy values (a stiffer strategy), 17 had recovered at least one TIP parameter within healthy values and 17 with both TIP parameters above healthy values (a compliant strategy). There were 2 subjects who had both parameters within healthy values.

Table 88: Correlations between hop performance (distance) and strategy (TIP and Kinematic change parameters) in subjects 1 year following ACLR and rehabilitation; there were large and significant correlations between parameters.

parameter	hop distance	TIP length change	TIP angle change	knee flexion	trunk lean
hop distance (m/height)	1	.577**	.722**	.527**	.602**
TIP length change (% leg length)	.577**	1	.862**	.940**	.908**
TIP angle change (°)	.722**	.862**	1	.842**	.796**
knee flexion (°)	.527**	.940**	.842**	1	.842**
trunk lean (°)	.602**	.908**	.796**	.842**	1

Key: Correlation coefficient – r, ** = Significant at P<0.001

Table 89: Hop distance for subjects 1 year following ACLR sub classified according to hop strategy below, within or above healthy parameters.

parameter	below healthy				within healthy				above healthy			
	n	mean	SE	SD	n	mean	SE	SD	n	mean	SE	SD
knee flexion (°)	36	.65	.04	.21	18	.74	.04	.18	20	.88	.06	.28
trunk lean (°)	36	.63	.03	.19	16	.73	.05	.19	22	.90	.06	.27
TIP length (% LL)	43	.63	.03	.20	6	.84	.04	.09	25	.88	.05	.26
TIP angle (°)	47	.66	.03	.20	9	.75	.03	.10	18	.93	.07	.28

Key: TIP length (% leg length), n = number of subjects, SE = Standard error of the mean, SD = standard deviation, TIP = telescopic inverted pendulum.

Table 90: TIP parameters for the three groups sub classified by landing strategy on the basis of TIP parameters.

Parameter	below healthy (n=40)			within healthy (n=17)			above healthy (n=17)		
	mean	SE	SD	mean	SE	SD	mean	SE	SD
TIP length at IC	116	0.5	3.3	118	1.8	7.6	115	1.8	7.5
TIP length at PKF	110	1.4	8.6	101	1.4	5.9	83	3.6	14.8
TIP length change	6	1.1	6.8	17	1.8	7.3	33	3.2	13.2
TIP angle at IC	78	0.7	4.4	73	0.8	3.4	70	1.5	6.0
TIP angle at PKF	83	0.9	5.6	84	1.2	4.8	92	1.8	7.4
TIP angle change	5	0.9	5.6	10	0.8	3.1	22	2.6	10.9

Key: n = number of subjects, SE = Standard error of the mean, SD = standard deviation, TIP = telescopic inverted pendulum, TIP length (% leg length), TIP angle (°), IC = Initial contact, PKF = peak knee flexion.

Subgroup differences in strategy – full, partial and failure to recover TIP change.

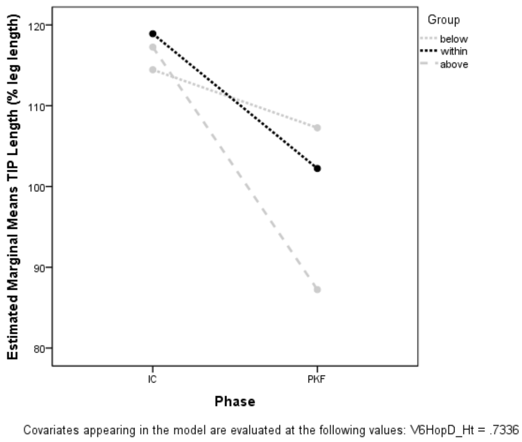
Repeated measures GLM identified significant interaction terms between group and phase for all TIP and kinematic parameters; TIP length ($F(2,70) = 32.568$, $P < 0.001$, Partial Eta Squared = 0.48); TIP angle ($F(2,70) = 16.559$, $P < 0.001$, Partial Eta Squared = 0.321); trunk lean ($F(2,70) = 21.358$, $P < 0.001$, Partial Eta squared = 0.379); and knee flexion ($F(2,70) = 29.211$, $P < 0.001$, Partial Eta Squared = 0.455). The interaction plots in Figure 50 clearly demonstrate the differences as the groups separated out on the plots for each of the variables. The groups therefore adopted different landing strategies. Those that remained below healthy TIP values continued to adopt the stiff TIP strategy similar to that of ACLD subjects, with a lower gradient between phases in the intercation plots. This is associated with the same upright trunk and less knee bend that was previously identified in the ACLD subjects. Those that recovered beyond healthy TIP values adopted a much more compliant TIP strategy with greater telescopic and pendular motion as demonstrated by the steeper gradient and longer lines in the TIP interaction plots. This was associated with increased knee bend at PKF and a steeper and longer plot. Most striking was the interaction at the trunk where there is greater forward trunk lean at IC and throughout the landing, demonstrated by the complete seperation of the plot at IC and steeper gradient to PKF. This is similar to the strategy adopted by the ACLD subjects who had recovered TIP strategy within healthy values. However unlike the ACLD subjects who continued with a stiff knee strategy, in the ACLR subjects there was also greater knee excursion.

These subgroup differences in TIP strategy are best illustrated when the TIP parameters are plotted against each other in Figure 51. The gradient and length of the lines demonstrates the average trajectory of the COG for each group during the hop landing. Photographic examples of these strategies at PKF are presented in Figure 52.

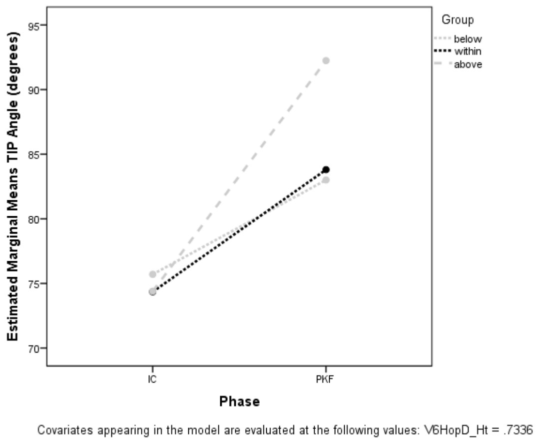
These strategy subgroups were further explored for differences in hop distance; descriptive statistics are presented in Table 91. ANOVA demonstrated that there was a significant effect of strategy on hop distance ($F(2,71) = 13.747$, $P < 0.001$). Post Hoc contrasts with Bonferroni correction showed that there were statistically significant differences in hop distance between those with a stiff strategy and both normal and compliant strategies, but not between normal and compliant strategies. Those with a stiff strategy therefore hopped less far than those with a compliant or normal strategy.

Figure 50: Interaction plots for Phase (IC and PKF on x axis) and Group (Healthy in black, Stiff in grey small dash and compliant in Grey large dash) for the TIP and Kinematic parameters in ACLR subjects sub classified by landing strategy.

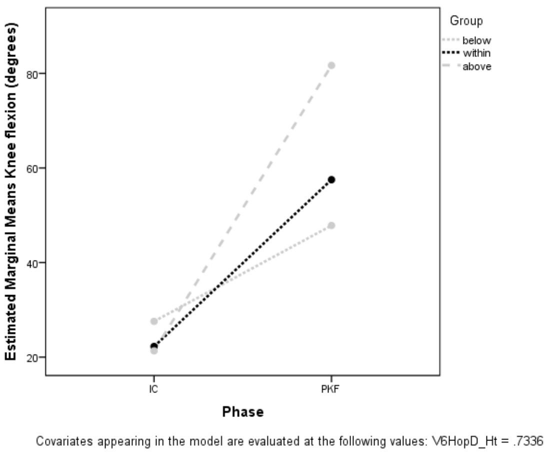
TIP length (% leg length)



TIP angle (°)



knee flexion (°)



trunk lean (°)

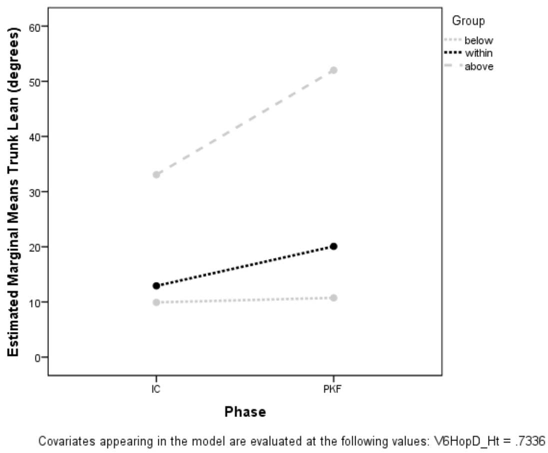


Figure 51: Illustration of the three identified landing strategies, Healthy (black), Stiff (grey small dash) and Compliant (grey large dash); TIP length (y) is plotted against TIP angle (x).

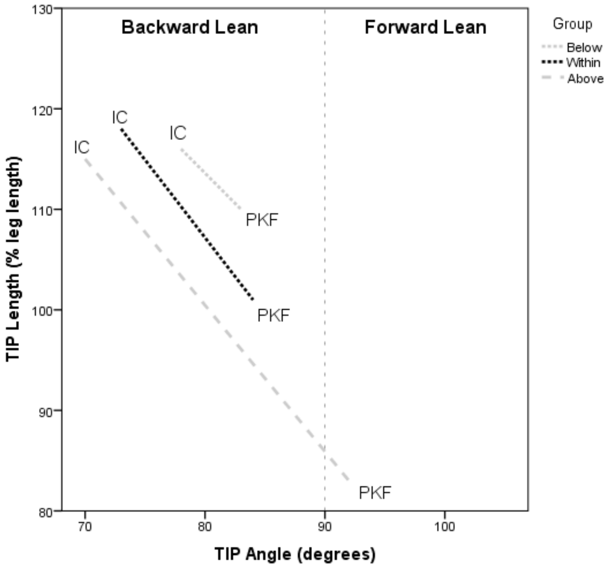


Figure 52: Examples of a compliant, healthy and stiff landing strategy at peak knee flexion

Compliant	**Healthy**	**Stiff**
Short TIP, flexed knee and forward trunk lean		Long TIP, miminal knee flexion and upright trunk

Key: COG = pink circle, TIP length and angle parameters calculate from the pink line, knee flexion = dark blue line, trunk lean = upper green line.

Table 91: Descriptive statistics for hop distance in ACLR subjects when sub classified by landing strategy, Stiff, healthy or compliant.

	n	mean	SD	SE	95% CI	
					lower	upper
Stiff	40	.63	.20	.03	.56	.69
Healthy	17	.78	.10	.03	.73	.83
Compliant	17	.94	.29	.07	.79	1.09

Key: n = number of subjects, SD = Standard deviation, SE = standard error of mean, CI = confidence interval.

In summary, a spectrum of hop strategies have been identified in the ACLR subjects, ranging from a stiff strategy similar to that seen in ACLD subjects to a compliant strategy characterised by greater TIP excursion. Poor hop performance was associated with a stiffer landing and good hop performance with the normal and compliant landing strategies. In the compliant landing strategy knee excursion returned to within healthy values; however there was an increase in forward trunk lean throughout the landing phase. This is likely to represent a compensatory strategy linked to improving performance and maintaining control of the COG.

A hierarchy of activity parameters

The hypothesised hierarchy was again apparent in the ongoing deficits for the injured limb of the ACLR group (Figure 53). Gait had the smallest deficits (6%), hop the greatest (18%) with squat intermediate (11%). Recovery within the clinical significance criteria is summarised in Table 92; there is again a hierarchy such that more subjects achieved recovery in gait than squat and more failed hop than squat. This provides further support for the presence of a hierarchy of functional tests within the ACLR population that may help guide task oriented rehabilitation strategies.

Figure 53: A hierarchy of mean deficits in activity parameters in the ACLR group when compared to healthy values, Gait has the smallest deficit, hop the greatest and squat is intermediate.

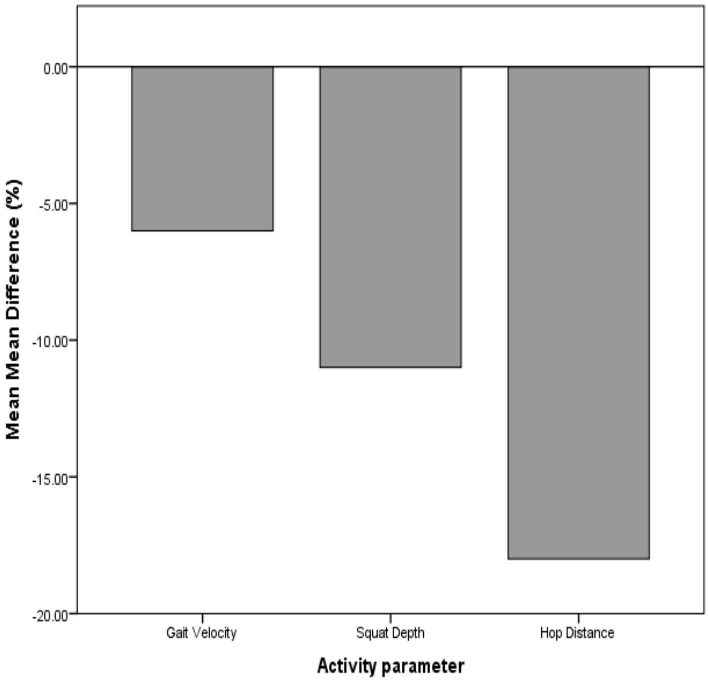


Table 92: Clinical significance criteria for the activity performance parameters and the number of ACLR subjects classified at each level of recovery.

		recovery		
		failure	**partial**	**full**
gait velocity (m/s)	**criteria**	<1.26		>1.325
	ACLR n	23	19	32
Squat PKF (°)	**criteria**	>105		<97.5
	ACLR n	37	14	23
hop distance (m/height)	**criteria**	<.76		>0.825
	ACLR n	41	9	24

Key: ACLR n = number of ACLR subjects categorised at that level.

Summary of results for question three.

Measures of knee function, participation and activities from a group of ACLR subjects 1 year following surgical reconstruction were explored in comparison to a matched healthy group. The null hypothesis for question three was rejected. There were significant deficits in functional performance and knee stability in subjects 1 year following ACL reconstruction in comparison to healthy subjects. These differences were demonstrated in all three domains of the WHO ICF.

Functional stability fully recovered in 46 subjects and participation to pre-injury levels in 25. From the perspective of functional coping, there were 20 copers, 26 adaptors and 28 who remained classified as non-copers. There were average deficits in knee function of 10% in comparison to age and gender matched healthy values and whilst 25 subjects were pain free, 42 continued to experience mild pain and 7 moderate or severe pain. All three activities remained limited on average, with slower walking, fewer squat repetitions with less peak knee flexion, reduced hop distance and a stiffer landing strategy. A spectrum of landing strategies from stiff to compliant has been identified. The stiff strategy is similar to that of ACLD subjects; however the compliant strategy is associated with recovery of knee flexion and coincided with increasing forward trunk lean throughout the landing phase. Stiff landings were associated with poor performance, whilst normal and compliant landing strategies were associated with greater performance. Deficits in performance were minimal for the non-injured limb, with recovery of non-injured hop performance occurring on average between 6 and 12 months from surgery. However strategy remained affected bilaterally. Classification of recovery of hop distance with limb symmetry indices underestimates recovery in comparison to the clinical significance criteria identified in this healthy cohort.

Themes

These findings add to the previously identified themes:

1. ACLD subjects demonstrated deficits in performance and altered strategy in three activities. There were significant average improvements 1 year following ACLR; however some subjects did not improve on clinical significance analysis. **There was variable recovery; however on average subjects were not recovered within the healthy comparison criteria.**
2. Deficits in functional performance and strategy in ACLD subjects were consistent with the hypothesised hierarchy. One year following ACLR, gait and hop performance improved in line with the hierarchy, however squat depth did not. **The deficits that remained in ACLR subjects when compared to healthy subject were consistent with the hypothesised hierarchy**

3. Deficits in ACLD subjects were bilateral, limiting the utility of symmetry standards. There were bilateral improvements in hop performance during the first year following ACLR, however squat depth deteriorated further on the non-injured limb. **At 1 year following ACLR, the non-injured limb had on average recovered hop distance, however bilateral alterations in landing strategy remained.**

Who was successful?

The number of subjects that recovered within healthy values for each of the primary parameters are summarised in Table 93. There is a hierarchy in the domains of the ICF such that stability recovery is most often successful, followed by participation, function and finally activity.

Table 93: Who was successful? Frequency distribution of subjects classified at each level of recovery for each of the primary outcome parameters.

ICF domain	parameter	success (number of subjects)		
		full	partial	fail
Functional Stability		46	16	12
Participation	Tegner	25	26	23
Function	IKDC SKF	19	19	36
Activity	gait velocity	32	19	23
	squat depth	23	14	37
	hop distance	24	9	41

However, the a priori agreed definition of success was “a functionally stable knee that permitted symptom free return to pre-injury activity”. A composite score generated from recovery of functional stability, function and participation within the healthy clinical significance criteria was therefore required. In order to achieve this, each of the parameters (stability, function and participation) was coded for recovery. Full recovery was scored 1, partial recovery at 0 and failure to recover -1. The composite score for success was then defined by the sum of the three parameters such that scores of 2 or more were defined as success, -2 or less as failure and between -1 and 1 as partial success. This meant that to be successful it was not possible to fail to recover on any of the parameters. Table 94 shows the correlations between the raw scores for the parameters, the clinical significance criteria for the parameters and the composite success parameter. All correlations were strong (r>0.7) and highly significant (P<.001) indicating that they were all saying the same thing; the composite success parameter was therefore representative of the measured parameters. Figure 54 shows this data graphically, with green representing full, amber partial and red failed to recovery. Using this composite parameter 26 subjects were considered fully successful, 20 partially successful and 28 that failed to meet the standard for successful recovery.

Figure 54: Defining success with a composite recovery parameter (bottom row). The parameter is constructed from functional stability, knee function and participation parameters. Each vertical bar represents an individual subject; success is coded as failure in red, partial recovery in amber and full recovery in green.

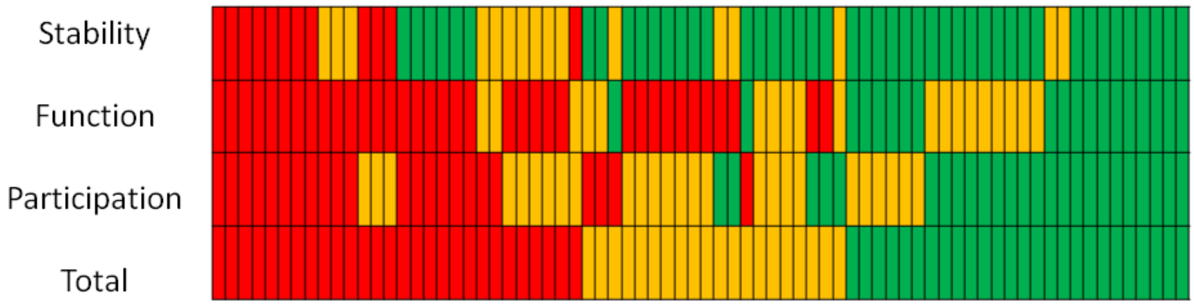


Table 94: Correlations between the composite success parameter and raw scores on each contributing parameter.

		Success	Stability		Function		Participation	
			raw	recovery	raw	recovery	raw	recovery
Success		1	.741**	.762**	.842**	.807**	.774**	.789**
Stability	**raw**	.741**	1	.965**	.704**	.425**	.423**	.388**
	recovery	.762**	.965**	1	.663**	.426**	.434**	.401**
Function	**raw**	.842**	.704**	.663**	1	.741**	.756**	.582**
	recovery	.807**	.425**	.426**	.741**	1	.599**	.454**
Participation	**raw**	.774**	.423**	.434**	.756**	.599**	1	.784**
	recovery	.789**	.388**	.401**	.582**	.454**	.784**	1

Question Four

Is it possible to predict success following ACLR?

Parameters that predict success at 1 year following ACLR are useful for informing intervention choices, particularly if they are modifiable through service redesign or rehabilitation intervention. Therefore, the data was analysed to identify relationships between parameters that might be predictors of success following ACLR. Firstly the injury and pathway characteristics were investigated to identify effects of injury severity and current service provision, followed by the activity performance parameters which might be useful clinical milestones for informing rehabilitation progression.

Correlations between success and the available injury and pathway characteristics are presented in Table 95. There were low (r<0.3) and non-significant (P>0.05) correlations between success and all of the injury / pathway parameters. Correlations between the activity parameters and success are presented in Table 96. There were low (r<0.3) and non-significant (P>0.05) correlations between success and the activity parameters. None of these variables were sufficiently correlated to be included in a stepwise regression model. It was therefore not possible to predict success following ACLR using the activity performance parameters that were proposed for use as clinical milestones within criterion based rehabilitation programmes. However, it would be of interest to the rehabilitation community to understand how pre-operative deficits and recovery of these activities relate to recovery of task performance at 1 year following surgery as this may guide rehabilitation from the perspective of performance recovery.

Table 95: Correlations between success 1 year following ACLR and rehabilitation and the injury / pathway characteristics; Correlations are small and not statistically significant.

	meniscal injury	time to surgery	prehabilitation	success
meniscal injury	1	.045	-.225	-.043
time to surgery	.045	1	-.002	.090
prehabilitation	-.225	-.002	1	.224
success	-.043	.090	.224	1

Key: Correlation coefficient = r

Table 96: Correlations between success 1 year following ACLR and the activity parameters before and 1 year after surgery.

time	parameter	success	gait velocity	squat depth	hop distance
pre-operative	**Success**	1	-.103	-.007	.050
	gait velocity (m/s)	-.103	1	-.344**	.047
	squat depth (°)	-.007	-.344**	1	-.324**
	hop distance (m/ht)	.050	.047	-.324**	1
1 year	**Success**	1	-.052	-.112	-.088
	gait velocity (m/s)	-.052	1	-.021	.113
	squat depth (°)	-.112	-.021	1	-.446**
	hop distance (m/ht)	-.088	.113	-.446**	1

Key: Correlation coefficient = r, * significant at P<0.05, ** significant at P<0.001.

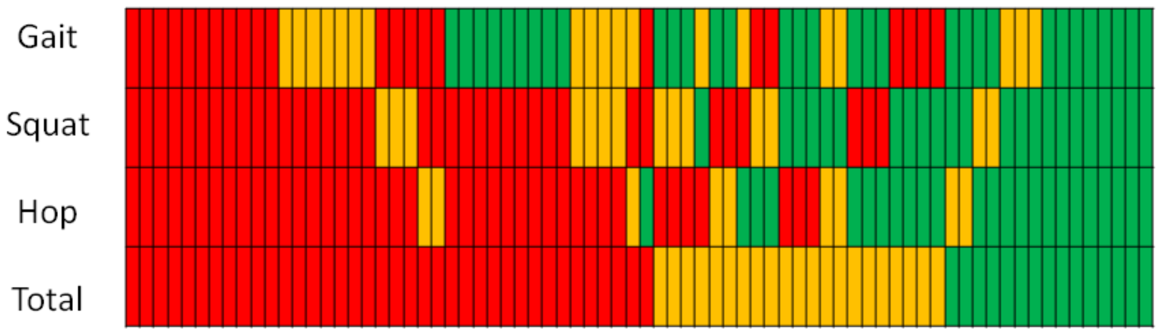
Is it possible to predict recovery of activity performance?

In order to define recovery across all three activities a composite score for activity recovery was required. The methods applied to the success criteria above were adopted, scoring recovered subjects 1 and failed subjects -1 for each activity and then coding the sum of these as recovered if 2 or more and failed if -2 or less. Correlations between the activity parameters and the composite parameter are displayed in Table 97. The correlations were highly significant (P<0.001) and moderately strong (r>0.4) with gait and strong (r>0.7) with both squat and hop demonstrating that the composite variable is appropriately measuring all three parameters. Figure 55 shows this data graphically, with green representing full, amber partial and red failed recovery of activity performance to healthy levels. When split on this variable 15 subjects were considered fully recovered, 21 partially recovered and 38 failed to recover healthy performance of the three activities.

Table 97: Correlations between the composite activity recovery parameter and performance variables at 1 year following ACLR and rehabilitation; there were strong and significant correlations.

	Statistic	recovery	gait	squat	hop
recovery	r	1	.459**	.773**	.769**
gait	r	.459**	1	.192	.123
squat	r	.773**	.192	1	.503**
hop	r	.769**	.123	.503**	1

Figure 55: Defining successful recovery of performance with a composite recovery parameter (bottom row). The parameter is constructed from gait velocity, squat depth and hop distance parameters. Each vertical bar represents an individual subject; success is coded as failure in red, partial recovery in amber and full recovery in green.



Recovery of activity parameters and predictors

Descriptive statistics for the three groups on the basis of the composite activity performance score are presented for the pre-operative data in Table 98 and displayed graphically over the time (longitudinal data) for the post-operatively data in Figures 56 to 58. There appears to be a clear pattern in the pre-operative data; those that failed to recover at 1 year following surgery showed mean deficits in all three activities in comparison to those that fully recovered. However, those that partially recovered showed deficits only in the more complex activity of hop for distance in comparison to those that fully recovered.

The groups appear divided across the longitudinal data, with those who perform better pre-operatively, continuing to do so throughout the recovery period. The means follow a predictable and separate trajectory for each group. Both the pre and post-operative activity performance therefore appears to be a useful consideration for predicting recovery at 1 year following surgery and will therefore be considered for entry into regression models.

Table 98: Activity performance at the pre-operative assessment in groups classified as recovered at 1 year following ACLR and rehabilitation; those that failed were worse off before surgery.

group	statistic	gait velocity	squat depth	hop distance
failed	mean	1.15	115	0.58
	SD	0.21	13	0.19
partial	mean	1.30	95	0.58
	SD	0.15	17	0.18
full	mean	1.31	95	0.71
	SD	0.11	10	0.17

Figure 56: Road to recovery for gait velocity; mean (solid line) +/- 0.5 SD (dashed line) for the three groups classified as recovered (green),partially recovered (amber) and failure (red) and the Healthy comparator group (black) across the longitudinal data following surgery; the groups overlap but the means remain distinct.

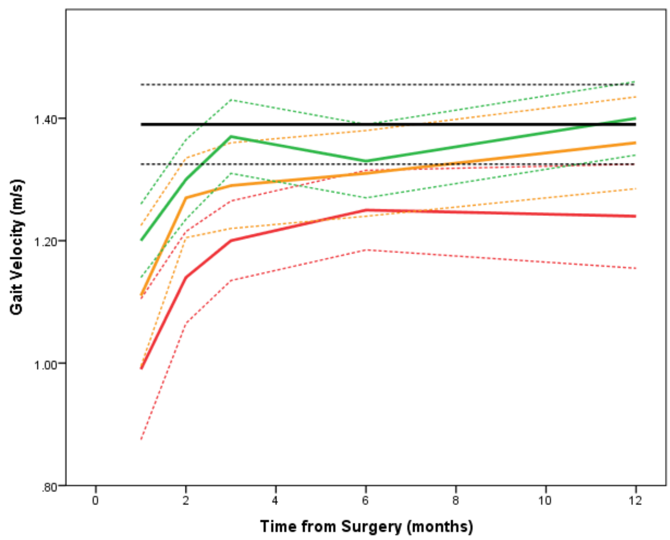


Figure 57: Road to recovery for squat depth; Mean (solid line) +/- 0.5 SD (dashed line) for the three groups classified as recovered (green),partially recovered (amber) and failure (red) and the Healthy comparator group (black) across the longitudinal data following surgery; The groups overlap but the means remain distinct.

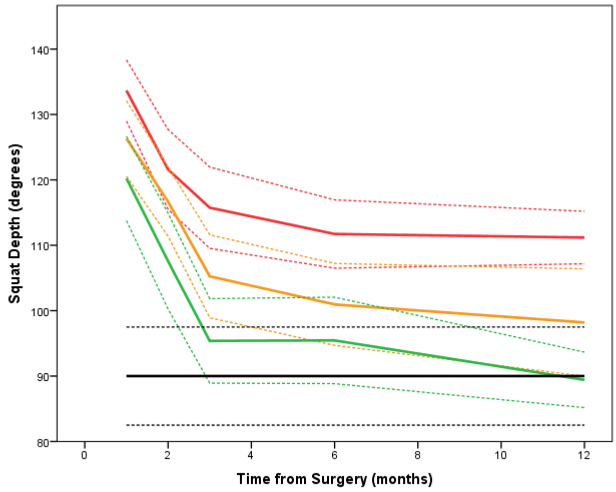
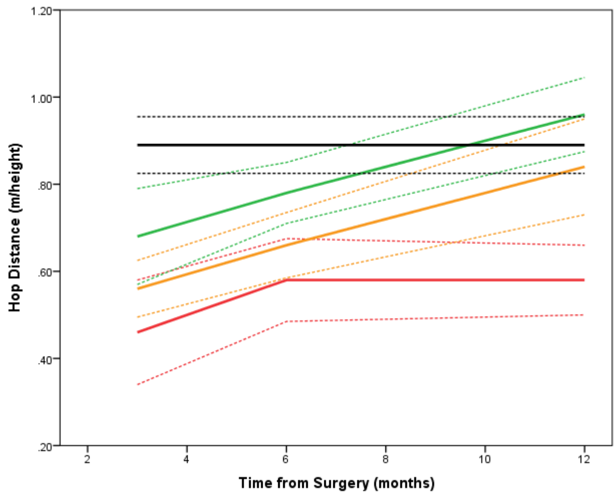


Figure 58: Road to recovery for hop distance; mean (solid line) +/- 0.5 SD (dashed line) for the three groups classified as recovered (green),partially recovered (amber) and failure (red) and the Healthy comparator group (black) across the longitudinal data following surgery; the groups overlap but the means remain distinct.



Pre-operative predictors

Gait velocity, squat depth and hop distance were entered into a stepwise regression model with activity recovery as the dependant variable (Table 99). The regression model demonstrated that pre-operative gait velocity and squat depth were predictors of activity recovery following ACLR; hop distance did not significantly add to the model. Together the two parameters accounted for 33% of the variance in activity recovery at 1 year following ACLR. The data required further investigation to identify appropriate cut off values that can be used as a target for pre-operative rehabilitation programmes. This was completed using ROC curve analysis and is reported in a later section.

Table 99: Regression model for the pre-operative predictors of successful recovery of activity performance.

model	parameter	beta	SE	standardised beta	t	sig.	R squared
1	constant	2.314	0.494		4.679	<.001	
	squat	-0.025	0.005	-0.535	-5.376	<.001	
2	constant	0.854	0.852		1.002	0.320	0.327
	squat	-0.021	0.005	-0.461	-4.449	<0.001	
	gait	0.894	0.430	0.215	2.079	0.041	

Model outputs

Correlations: gait r =.374, Squat r = -0.535, Hop r = 0.235.
R = 0.572, R^2= 0.327, Adjusted R^2= 0.308, R^2change F(1,71) = 4.323 P = 0.041.
Diagnostics are all appropriate: Durbin Watson = 1.974, Tolerance = 0.882 and VIF = 1.134 2 with residuals > 2 (2.062 and 2.156), Max Cooks distance = 0.096, Max Leverage = 0.160.
There is no sign of heteroscedasticity, non-linearity or lack of normality in the plots.

Post-operative predictors

With data collected at 4 different times following surgery (1, 2, 3 and 6 months), the first step was to identify the post-operative time at which each of the activity parameters was most predictive of recovery at 1 year post-operatively. It was hypothesised on the basis of the hierarchical nature of the tasks and their recovery following surgery, that gait parameters would be most useful in the early post-operatively period and the hop later on. Once the timing was selected a multivariable model with the activity parameters could be proposed and tested.

The time periods following surgery are defined as follows:

Visit 1 (V1) = Pre-operative

Visit 2 (V2) = 1 month following surgery

Visit 3 (V3) = 2 month following surgery

Visit 4 (V4) = 3 month following surgery

Visit 5 (V5) = 6 month following surgery

Gait

Table 100 shows the results when gait velocity at V2 and V3 were regressed on activity recovery using stepwise methods. V2 did not meet the entry requirements of the model (Beta = .171, t = 1.334, P>0.10). V3 was a significant predictor, explaining 26% of the variance in activity recovery at 1 year following surgery. The assumption of independent errors was not supported by the Durbin Watson statistic; however all other assumptions and distributional requirements were supported.

Table 100: Regression model for gait velocity at V2 and V3 to predict activity recovery at V6.

model	parameter	beta	SE	standardised beta	t	sig.	R squared
1	constant	-3.144	.650		-4.838	<.001	0.212
	V3 Gait	2.346	.534	.460	4.395	<.001	

Model outputs
Correlations: V2 r = 0.382 and V3 r = 0.460.
R = 0.460, R^2= 0.212, Adjusted R^2= 0.201, R^2change F(2,71) = 19.317 P <.001.
Diagnostics are all appropriate: Durbin Watson = 0.383, Tolerance 1.000, VIF = 1.00, max Cooks distance = 0.087 and max Leverage <0.108. There are 3 residuals > 2 (2.013, 2.040 and 2.390). There is no sign of heteroscedasticity, non-linearity or lack of normality in the plots.

Squat

Table 101 shows the results when squat depth at V3 and V4 were regressed on activity recovery. V3 did not meet the entry requirements of the model (Beta = 0.006 t = 0.044 P > 0.10). V4 was a predictor, explaining 29% of the variance in activity recovery. The assumption of independent errors was not supported by the Durbin Watson statistic; however all other assumptions and distributional requirements were supported.

Table 101: Regression model for squat depth at V3 and V4 to predict activity recovery at V6.

model	parameter	beta	SE	standardised beta	t	sig.	R squared
1	constant	2.858	0.578		4.945	<.001	0.298
	V4	-0.029	.005	.546	-5.533	<.001	

Model outputs
Correlations: V3 r = 0.400 and V4 0.546.
R = 0.546, R^2= 0.298, Adjusted R^2= 0.289, R^2change = 0.298 F(2,71) = 30.609, P<.001.
Diagnostics are all appropriate: Durbin Watson = 0.582, Tolerance = 0.455, VIF = 2.198.
There are 2 standardised residuals > 2 (2.544 and 2.107), Max Cooks distance = 0.084, Max Leverage = 0.088. There is no sign of heteroscedasticity or non-linearity or non-normality in the plots.

Hop for distance

Table 102 shows the results when hop distance at V4 and V5 were regressed on activity recovery. V4 did not meet the entry requirements of the model (Beta = 0.006, t = 0.044 P > 0.10). V5 was a predictor, explaining 18% of the variance in activity recovery. The assumption of independent errors was not supported by the Durbin Watson statistic, however all other assumptions and distributional requirements were supported.

Table 102: Regression model for hop distance at V4 and V5 to predict activity recovery at V6

model	parameter	beta	SE	Standardised beta	t	sig.	R squared
1	**constant**	-1.499	0.303		-4.949	<.001	0.188
	V5	1.850	0.453	0.433	4.081	<.001	

Model outputs
Correlations; V4 hop r = 0.375 P= 0.001 and V5 r = 0.433, P <.001.
R = 0.433, R^2 = 0.188, Adjusted R^2= 0.177, R^2change = 0.188 F(2,71) = 16.655 P<0.001.
Diagnostics are all appropriate: Durbin Watson = 0.437, Tolerance = 0.384 VIF = 2.607. There are 2 standardised residuals > 2 (2.317 and 2.100), max. Cooks distance = 0.435 and max. Leverage = 0.111. There is no sign of heteroscedasticity or non-linearity or non-normality in the plots.

In summary, the activity parameters were all able to predict activity performance 1 year following surgery. The variables were entered at time points hypothesised to be most appropriate according to the hierarchy of difficulty and recovery that has been identified. It is interesting to note that it was the latter of the two time intervals that was sufficiently highly correlated to meet the requirements of model entry. This suggests that recovery to a level where prediction is possible is taking longer than previously appreciated. Gait velocity at 2 months and squat depth at 3 months were the strongest predictors accounting for 26 and 29% of the variance in 1 year activity performance. Hop distance at 6 months was less strong accounting for 18% of the variance. These variables will now be entered into a multivariable model regressed on activity performance at 1 year following surgery.

Model for predicting activity recovery following ACLR

Results for the multivariable regression of gait at V3, squat at V4 and Hop at V5 on activity recovery are presented in Table 103 Hop did not make the requirements for entry into the model (Beta 0.086, t = 0.699, P = 0.487). V3 gait and V4 squat were significant predictors of activity recovery; together they explain 35% of the variance in activity recovery. The assumption of independent errors was not supported by the Durbin Watson statistic, however all other assumptions and distributional requirements were supported.

Table 103: Regression model for gait (V3), squat (V4) and hop (V5) for predicting activity recovery at V6.

model	parameter	beta	SE	standardised beta	t	sig.	R squared
1	Constant	2.858	0.578		4.945	<0.001	
	V4 squat	-0.029	0.005	-0.546	-5.533	<0.001	
2	Constant	0.400	1.019		0.393	0.696	0.371
	V4 Squat	-0.023	0.005	-0.433	-4.244	<0.001	
	V3 gait	1.492	0.521	0.292	2.866	0.005	

Model outputs

Correlations; Gait V3 r = 0.460, Squat V4 r = -5.46 and Hop V5 r = 0.433.
R = 0.609, R^2= 0.371, Adjusted R^2= 0.353, R^2change F(1,71) = 30.609, P=0.005.
Diagnostics are all appropriate: Durbin Watson = 0.729, Tolerance = 0.594, VIF = 1.685,
There are three standardised residuals > 2 (2.023, 2.012 and - 2.267) and one >2.925.Max. Cooks distance = 0.108, max. Leverage = 0.100. There is no sign of heteroscedasticity or non-linearity or non-normality in the plots.

In summary, gait velocity 2 months following surgery and squat depth 3 months following surgery were significant predictors of recovery of activity performance at 1 year following ACLR, accounting for 35% of the variance in outcome. Further exploration of these parameters to define the values at which full recovery is predicted was required to make this information clinically applicable. This was completed using Receiver Operating Characteristic (ROC) curve analysis.

Defining the cut off for pre and post-operative predictors of activity performance at 1 year following surgery.

Table 104 shows the cut off values on each activity parameter at each time point which corresponded to the highest sum of sensitivity and specificity (i.e. where the fewest misclassifications occurred). The ROC curves for each activity parameter at the time periods they were entered into the regression models are displayed in Figure 59. The cut off values correspond to the point on the graph closest to the top left hand corner of the graph. The cut off for the identified pre-operative predictors of activity recovery is 1.26 m/s for gait and 105 degrees for squat depth. For failure to recover they are 1.14 m/s for gait and 106 degrees for squat depth. It is therefore possible to propose that prior to surgery subjects with a gait velocity >1.26m/s and a squat depth <105 degrees are more likely to recover activity performance 1 year following surgery than those that do not meet these criteria. Conversely, those with gait velocity <1.14 and squat depth > 106 degrees are more likely to fail to recover activity performance 1 year following surgery. These cut off points might act as useful goals for pre-operative rehabilitation programmes.

The cut off scores for the identified post-operatively predictors are:

- Gait velocity at 2 months following surgery >1.28 m/s for full recovery and <1.25m/s for failure to recover.
- Squat depth at 3 months following surgery < 98 degrees for full recovery and >106 degrees for failure to recover.

The cut off scores for failure and full recovery at each of the longitudinal data points has been plotted in Figures 60 to 62. It is proposed that these graphs offer a tool by which reasonable predictions of recovery may be facilitated and that progress against these could be measured in order to inform rehabilitation progression decisions.

The predictors and recovery plots presented thus far all suggest that the recovery groups were defined in the preoperative and early post-operative period. This suggests that individuals were not changing subgroups as they progress through the rehabilitation process. This was investigated at the individual level by applying the ROC derived cut off for gait and squat parameters to each individual at each point in the longitudinal data. This data is displayed graphically in Figure 63, again using green to identify full recovery, amber partial recovery and red failure to recover. The data clearly demonstrates the lack of movement between these recovery groups throughout the rehabilitation process. There is only one person who passed the pre-operatively criteria and failed overall and only one person failing pre-operatively who passed overall. It seems that in terms of activity recovery, outcome is currently influenced in the preoperative phase.

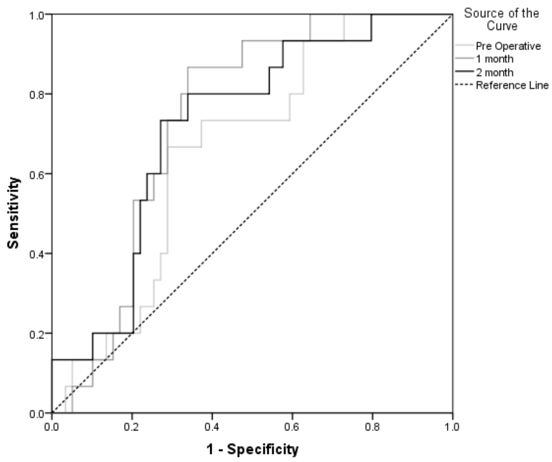
Table 104: Identifying levels for each parameters for use as clinical milestones; ROC cut off for groups classified as recovered and partially recovered for activity success at 1 year following ACLR and rehabilitation.

		recovered						not recovered					
	Visit	Cut	Sens	Spec	Sum	AUC	Sig	Cut	Sens	Spec	Sum	AUC	Sig
gait velocity (m/s)	1	1.26	.73	.63	1.36	.66	.054	1.14	.92	.45	1.36	.73	.001
	2	1.10	.87	.66	1.53	.74	.004	1.01	.78	.63	1.41	.70	.002
	3	1.28	.73	.63	1.46	.72	.009	1.25	.72	.82	1.54	.77	<.001
	4	1.24	.93	.54	1.48	.76	.002	1.24	.81	.68	1.49	.76	<.001
	5	1.23	.87	.49	1.36	.62	.137	1.23	.75	.53	1.28	.64	.040
	6	1.30	.93	.58	1.51	.76	.002	1.31	.69	.74	1.43	.75	<.001
squat depth (degrees)	1	105	.87	.64	1.51	.77	.001	106	.83	.82	1.65	.87	<.001
	2	129	.80	.66	1.46	.75	.004	131	.75	.76	1.41	.74	<.001
	3	105	.60	.95	1.55	.75	.003	110	.50	.82	1.32	.69	.005
	4	98	.67	.86	1.53	.81	<.001	106	.69	.92	1.51	.78	<.001
	5	99	.73	.80	1.53	.77	.001	99	.58	.95	1.53	.78	<.001
	6	97	.87	.86	1.73	.88	<.001	104	.81	.87	1.67	.86	<.001
Hop dist (m/height)	1	.76	.53	.85	1.38	.71	.013	.63	.53	.66	1.19	.58	.241
	4	.54	.80	.60	1.39	.72	.008	.40	.94	.47	1.42	.70	.003
	5	.64	.93	.61	1.54	.81	<.001	.62	.75	.66	1.41	.73	.001
	6	.78	1.00	.78	1.78	.89	<.001	.76	.72	.89	1.62	.90	<.001

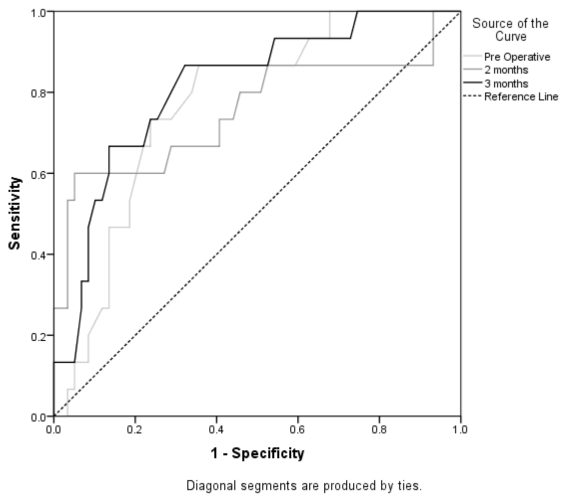
Key: Sens = Sensitivity, Spec – Specificity, Sum = sum of specificity, AUC = Area under the ROC curve. Cut off is selected at the value with the highest sum of spec + sens, when 2 or more values have the highest sum, the value with the highest spec is selected (i.e. lowest false positive rate).

Figure 59: ROC curves for each activity parameter when predicting success of activity recovery at 1 year following ACLR.

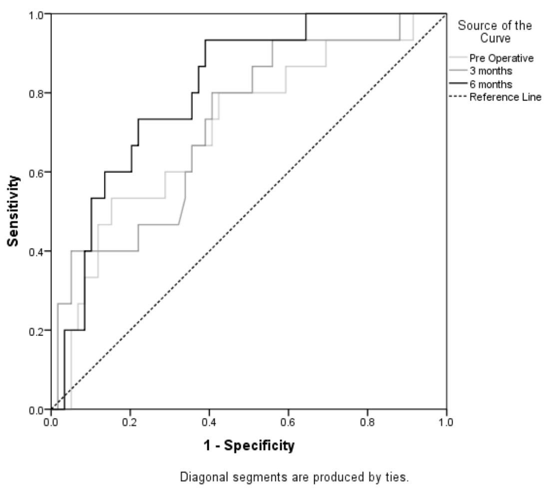
Gait



Squat

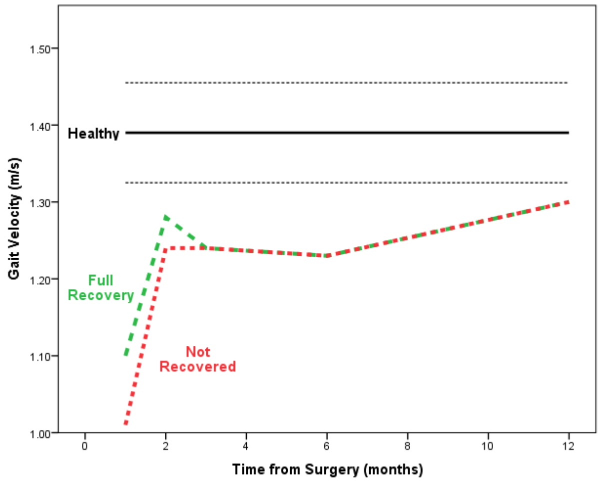


Hop



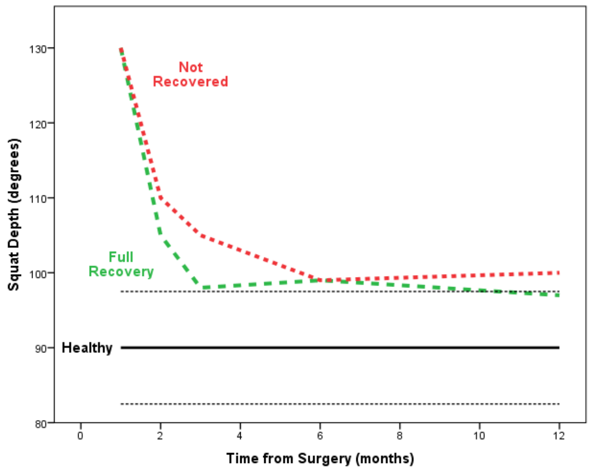
Key: In ROC curves, sensitivity (y axis) is plotted against 1-specificity (x axis) for each level of the variable. The point nearest the top left corner of the graph therefore represents the value which carries the greatest specificity and sensitivity for predicting success in activity recovery at 1 year following ACLR and is selected as the cut off for clinical testing.

Figure 60: Post-operative clinical milestones for gait velocity generated through ROC cut off when predicting success and failure for activity recovery at 1 year following ACLR.



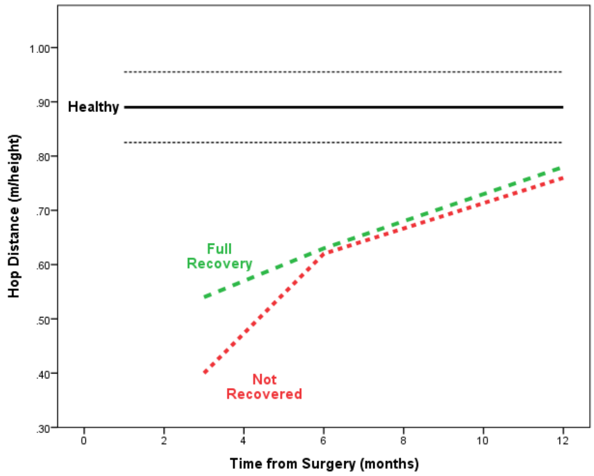
Key: The ROC cut off scores for gait velocity are presented at each of time period of the longitudinal data. A score above the green line would predict success and below the red line predict failure at 1 year post-operatively.

Figure 61: Post-operative clinical milestones for gait velocity generated through ROC cut off for squat depth when predicting success and failure for activity recovery at 1 year following ACLR



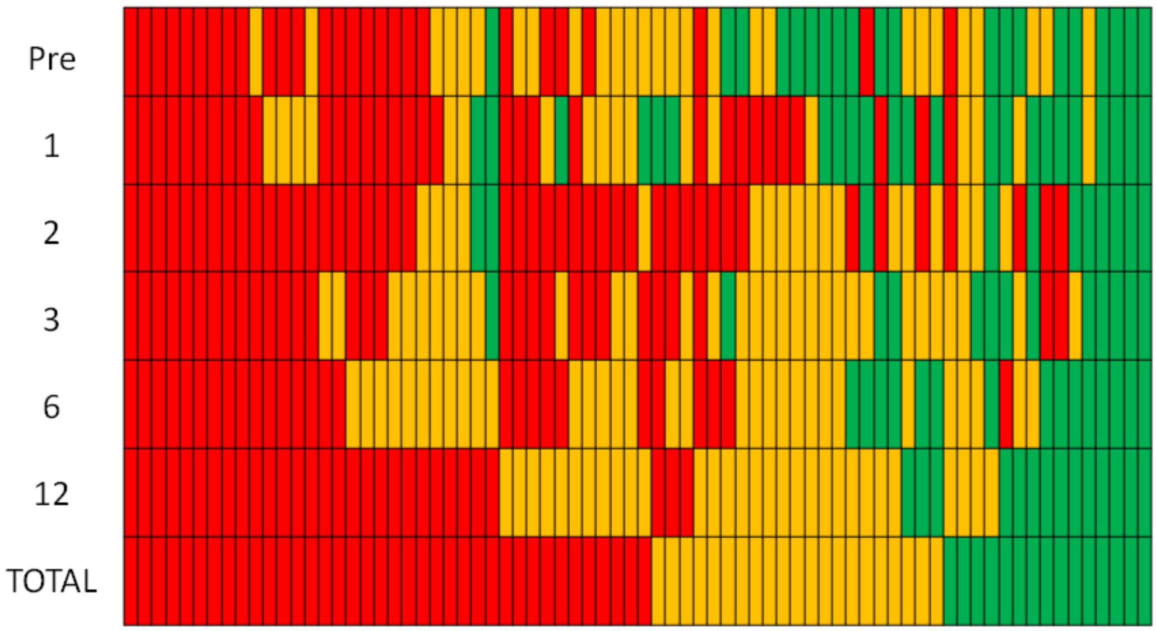
Key: The ROC cut off scores for squat depth are presented at each of time period of the longitudinal data. A score below the green line would predict success and above the red line predict failure at 1 year post-operatively. Note scoring is reversed when compared to gait and hop data.

Figure 62: Post-operative clinical milestones for gait velocity generated through ROC cut off for hop distance when predicting success and failure for activity recovery at 1 year following ACLR



Key: The ROC cut off scores for hop distance is presented at each of time period of the longitudinal data. A score above the green line would predict success and below the red line predict failure at 1 year post-operatively

Figure 63: Recovery at each stage of the longitudinal data using the ROC cut off scores for gait and squat; there was little movement between the classifications through the rehabilitation period.



Key : Red indicates faillure for both squat and gait, Amber indicates partial success with pass for one and fail for the other, Green indicates successful pass of both squat and gait.

Summary of predictors

It was not possible to predict success as defined by this study using injury, pathway or activity performance parameters. Predicting recovery of activity performance within healthy values defined by clinical significance criteria was however possible using individual activities in the pre-operatively and early post-operatively period. Gait velocity and squat depth were significant predictors, together explaining 33% variance in the final functional outcome when assessed pre-operatively and 35% when assessed at 2 and 3 months following surgery respectively. Values for both variables at which full recovery and failure to recover can be defined were determined by ROC curve analysis and are proposed as criterion to guide rehabilitation. Overall, there was little change from the trajectory determined prior to surgery, it seemed that current rehabilitation does not influence recovery sufficiently to change this trajectory and may therefore represent natural recovery process.

Themes

These findings add to the previously identified themes:

1. ACLD subjects demonstrated deficits in performance and altered strategy in all three activities. There were significant average improvements 1 year following ACLR; however some subjects did not improve on clinical significance analysis. There was variable recovery, however on average subjects were not recovered within the healthy comparison criteria. **The preoperative and early post-operative deficits in gait and squat were significant predictors of the post-operative recovery of activity performance.**
2. Deficits in ACLD subjects were bilateral, limiting the utility of symmetry standards. There were bilateral improvements in hop performance during the first year following ACLR; however squat depth deteriorated further on the non-injured limb. At 1 year following ACLR, the non-injured limb had on average recovered hop distance; however strategy remained significantly different from healthy bilaterally.
3. Deficits in functional performance and strategy in ACLD subjects were consistent with the hypothesised hierarchy. One year following ACLR, gait and hop performance improved in line with the hierarchy, however squat depth did not. The deficits that remained in ACLR subjects when compared to healthy subject were consistent with

the hypothesised hierarchy. **The least challenging tasks in the hierarchy were also the strongest predictors of activity performance 1 year after surgery.**

Summary of study findings

The null hypothesis for questions 1, 2 and 3 were all rejected. Statistically and clinically significant deficits in comparison to healthy values were identified in functional performance and knee stability prior to surgery. There was a statistically and clinically significant improvement by 1 year following surgery. However, statistically significant deficits from healthy remained at 1 year following surgery and many individuals failed to recover within the healthy clinical significance values.

Restrictions in both performance and strategy were identified in all three activities. The hypothesised hierarchy of task difficulty was confirmed; gait was simpler and hop more complex with single leg squat intermediate. Although the restrictions were greater on the injured limb, they were found to affect both limbs which had implications for interpretation of limb symmetry indices. The recommended limb symmetry criteria underestimated the deficits that were identified by healthy comparison and clinical significance criteria. A spectrum of landing strategies was identified using the 2D TIP tool, ranging from a stiff landing with minimal knee and trunk motion to a compliant landing with excess forward trunk lean. Relations with performance were identified that suggest the presence of compensatory strategies aimed at improving performance.

It was not possible to predict successful recovery as defined by a functionally stable knee that allows a symptom free return to pre-injury participation using the available parameters. However, the activity performance parameters proposed for use as clinical milestones, were able to predict recovery of activity performance at 1 year following surgery. Gait velocity and squat depth in the pre-operative and early post-operative period were the strongest predictors and values corresponding to full and failed recovery have been identified.

Discussion

This chapter will discuss the methods of the study, their limitations and implications for the interpretation of the data. Each research question will then be discussed in relation to the available literature and theory of recovery and rehabilitation. Throughout the discussion proposals and recommendations for clinical practice and further research will be made.

Methodological considerations

This section will discuss results of the recruitment process before moving on to the characteristics of the final sample, the matching process and implications for the analysis and interpretation. The injury characteristics and pre-operative pathway will be discussed and related to the wider ACL literature.

Recruitment and sampling

The study successfully recruited 85 and retained 74 subjects. Although this was slightly lower than the targeted 100, it was adequate for the sample size requirements of the analysis. A breakdown in the referral process led to potential participants being identified after surgery. The recruitment period was extended, however this was unable to fully compensate for the interruption. Exclusions after surgery were due to additional surgical intervention. Both of these factors represented a process of random sampling and therefore did not represent a threat to selection bias.

The study was very inclusive in sampling the local ACLR population, including all primary ACLR's unless there were significant comorbidities or concomitant injuries. This was considered important to reflect the broad spectrum of individuals treated within this service and is reflected in the distribution of the demographic and pre-injury participation data. The long time to surgery (19 months), low participation rate in pre-surgery rehabilitation (45%) and classification of 71 subjects as non-copers and just 3 as adaptors confirms the expectation that the sample represents those subjects who do not recover or adapt to injury. In this regard they are considered the worse off ACLD subjects at the highly symptomatic end of the spectrum seen within ACLD. It is anticipated that this is not an uncommon scenario within current NHS services (Bollen et al., 2010; Aratsu et al., 2015) however these factors will require consideration when applying results to different cohorts of people.

The healthy group were recruited throughout the data collection period. Whilst every effort was made to recruit a healthy sample that was hypothesised to be equivalent to the study population, this did not result in completely matched samples. Attempts were made to redress this; however this proved difficult within project constraints. Consequently, steps were taken to account for the small differences in sample characteristics using statistical solutions during the analysis.

Matching sample characteristics

Both the healthy and ACLD samples were predominantly male, in their early 30's and recreationally active in sports prior to injury. Matching for age and height was successful; however they were not completely matched for gender, body mass and participation. Although these differences were statistically significant they were of a small effect size and the distribution of the parameters suggests that matching was adequate. There was a trend ($P<0.01$) towards a larger number of females in the healthy group, again this was of a small effect size (ES =0.16) and any bias might be accounted for by including mass as a covariate and normalising to height. Differences in participation were of a moderate effect size (ES = 0.43), however this was less than the smallest detectable change (SDC) and is therefore of questionable clinical significance. The groups were considered adequately matched.

Healthy group activity parameters

Comparison of the activity performance parameters to published data confirms that the healthy cohort were representative of the wider healthy population. Since performance in gait (Bohannon and Andrews, 2011) and hop (Reid et al., 2007; Gustavsson et al., 2006; Itoh et al., 1998) is known to be affected by gender, particular reference is made to this and the small group differences in gender in this study. Mean gait velocity was 1.39m/s (SD 0.13) with no significant difference between males (M = 1.39 SD = 0.14) and females (M = 1.39 SD = 0.14). This is in agreement with the data presented by both Perry and Burnfield (2010) (M = 1.36 m/s) and Bohannon and Andrews (2011) (male 1.34 m/s to 1.43 m/s, female 1.24 m/s to 1.39 m/s). The performance of females therefore closely resembles healthy male performance, and provides reassurance regarding concerns about gender matching.

squat depth was symmetrical with a mean of 90 degrees (SD = 15). This is in agreement with both Zeller et al. (2003) and Weeks et al. (2003), however it is less than Beutler et al. (2003) and greater than Dwyer et al. (2010), see Table 105. Differences in task execution are likely to explain this, Beutler et al. (2003) allowed arms to be fixed on an external support which is likely to assist balance and control. There were no gender differences in this sample, which is in contrast to all other studies. Whilst this was not entirely expected, it did give further reassurance with respect to concerns about gender matching between groups. Symmetrical performance was confirmed as a feature of single leg squat performance and provides justification for use of the dominant limb as the comparator.

Table 105: Published values for peak knee flexion (degrees) during single leg squat in healthy subjects

Study	n	Male	Female	Sig
Beutler et al., 2002	18	120 +/- 21	96 +/- 19	<0.05
Zeller et al., 2003	18	90 +/- 6	95 +/- 6	0.292
Dwyer et al., 2010	44	67 +/-10	60 +/-13	<0.05
Weeks et al., 2012	22	86 +/-13	72 +/-7	0.001

Note: Weeks et al. (2012) report an overall PKF of 80 +/- 12 (range 57 – 110).

Mean hop distance was 0.89 x height (SD 0.13) which can only be directly compared to Roos et al. (2013) who reported 0.78 (+/-.14). The greater number of female subjects in that group is likely to explain the small difference in an otherwise similar group. The absolute hop distance was 1.56m (SD 0.26), which is similar to that of Paterno and Greenberger (1996), Gustavson et al. (2006) and van der Harst (2007). It is however considerably shorter than reported by Ageberg et al. (2001), Itoh et al. (1998), Matacolla et al. (2002) and O'Donell et al. (2006). See Table 106 for summary of published data. These differences seem to be explained by considerably younger (Itoh et al., 1998; Matacolla, 2002) or more active (Ageberg et al., 2001) cohorts. Whilst the healthy cohort are at the lower end of healthy performance and therefore considered a conservative estimate of healthy hop distance, they are within published values. Normalising hop distance to subject height helped to account for small gender differences which are likely to explain the lower hop distance. In agreement with previous studies of symmetry in healthy individuals (Ageberg et al., 1998; Petschnig et al., 1998; van der Harst, 2007; Gokeler et al., 2010), there were no significant differences in performance between limbs in healthy subjects, indicating that symmetry is a feature of healthy hop performance. However, they were more symmetrical than the 85% LSI standard (Barber et al., 1990), most achieve the 95% criterion (Thomeé et al., 2012).

Table 106: Published values for hop distance in healthy subjects

Study	Gender	hop distance (m)
Paterno and Greenberger 1996	Both	1.50 +/- .23
Gustavson et al., 2006	F	1.37 +/- .13
	M	1.60 +/-.11
	Both	1.51 +/- .16
Itoh et al., 1998	M	1.93 +/-.19
	F	1.49 +/-.14
Ageberg et al., 2001	Both	2.03 +/- .21
Matacolla et al., 2002	Both	1.88 +/-.29
O'Donnell et al., 2006	Both	1.75+/-.50
Van der Harst et al., 2007	Both	1.43 +/-70
Gokeler et al., 2010	Both	1.43 +/-.68
Baltaci et al., 2012	M	1.77 +/-.12

The ACLD sample

The ACLD sample represents the worse off ACLD subjects, presenting a long time following injury, with high symptom frequency and severity, high rates of meniscal injury and low participation in structured rehabilitation. As such they will be in contrast to much of the previous literature and represent an opportunity to study recovery in those most severely affected. These aspects will be further discussed.

Injury characteristics

Whilst there were a few subjects with signal changes in other ligaments on MRI, all were considered intact and stable during manipulation under anaesthesia at the time of surgery and were therefore considered to represent low grade injuries. All knees were unstable to Lachmans and all but 2 to pivot shift at MUA. There were a few low grade chondral injuries and bone bruises demonstrated on MRI. Minor chondral lesions (<Grade 1) have no significant effect on short term function after ACL injury (Hjermundrud et al., 2010). Bone bruise is known to resolve over the time frame of this study (Unay et al., 2009; Vincken et al., 2005) and to correlate poorly to symptoms beyond 6 months from injury (Szkopeg et al., 2012; Vincken et al., 2005). Neither injury was therefore considered an important factor in

short term recovery in this sample. There is however evidence that both of these injuries may be important precursors to osteoarthritis and therefore requires consideration in longer term follow-up studies (Nakamae et al., 2006; Magnussen et al., 2013).

The discrepancy in diagnosis of meniscal injury by MRI and arthroscopy was consistent with reports in the literature (Crawford et al., 2007). Arthroscopy is considered the gold standard diagnostic tool (Crawford et al., 2007); therefore this data was used in the analysis. The incidence of meniscal injury is very high (68% of subjects) compared to both the Swedish (49%) and American Keiser Permanente (63%) ACLR registers (Granan et al., 2012). It is however comparable with the literature regarding acquired medial meniscus injuries in chronic ACL deficient subjects (Barenius et al., 2014; Papastergiou et al., 2007; Church et al., 2005; O'Conner et al., 2005; Tandogan et al., 2004) and suggests that time from surgery may be a factor explaining the higher rate of meniscal tears. The high frequency (73%) and severity of functional instability is another factor suggesting a high risk for acquired meniscal injury (Tayton et al., 2009). An alternative view would be that the meniscal injuries occurred at the time of ACL injury and that the resulting loss of structural stability leads to high levels of functional instability and poor function. The data from this study is unable to further inform this debate, however it will be important to gain a better understanding of this if acquired meniscal injuries are to be understood and prevented.

Time to surgery

The lack of a structured pathway for ACL injured subjects was expected to result in a significant time delay between injury and surgery. The mean of 19 months (SD = 17) between injury and surgery confirms this expectation and is consistent with previous reports from UK NHS emergency departments (Bollen, 2000). Whilst delay is suggested as a possible risk factor for acquired meniscal injury, in contrast to published literature (Papastergiou et al., 2007; O'Conner et al., 2005; Tandogan et al., 2004) there was no significant correlation between time to surgery and the incidence of meniscal injuries ($r=0.011$, $P>0.05$) and no difference in meniscal injury rates in those undergoing surgery within early (<6 months) or delayed (>12 months) time scales. The lack of subjects receiving surgery within these earlier timescales where acquired meniscal injury is thought to occur (Papastergiou et al., 2007; O'Conner et al., 2005; Tandogan et al., 2004) may be a factor explaining this finding. The data does however offer some support to the earlier proposal that meniscal injuries sustained at ACL injury may be an important structural factor for this non-coping sample.

Whilst there is evidence that time to surgery may influence function outcomes following ACLR (Laxdal et al., 2005; Ahlen et al., 2011), no investigations of effect on pre-operative function were identified. In this sample there was no correlation between time to surgery and any of the pre-operative function parameters. The lack of subjects receiving surgery early after injury and the highly symptomatic nature of the subjects may be factors explaining this. The data suggests that whilst there was no apparent negative impact of delay on these outcomes, there was also no reason to delay surgery on the basis of requiring recovery of these parameters. Further questions arise as to what the subjects were doing during this period between injury and surgery, if this was being used for rehabilitation, or if subjects were attempting to cope with, or adapt to, the injury. Early identification of this patient group when they attend the emergency department and development of a structured pathway such as that described by the Delaware group (Logerstedt et al., 2012) and some local NHS services (Jibuike et al, 2003) would speed up the care of these people and may have positive impact on outcomes.

Pre-operative rehabilitation

Under half of the sample (45%) reported participation in rehabilitation between injury and surgery. The measurement of rehabilitation was based only on patient recollection of participation in rehabilitation and may therefore include recall bias. It does however seem reasonable to believe that subjects who completed and failed a comprehensive goal oriented rehabilitation programme as described in the literature (Logerstedt et al., 2013; Hartigan et al., 2009) would recall this. Subjects are often identified late after injury and usually when symptomatic with recurrent instability and it appears that rehabilitation is often not considered to be a viable intervention. Since all ACLD subjects are expected to benefit from pre-operative rehabilitation (Hartigan et al., 2009; Frobell et al., 2010; Logerstedt et al., 2013) irrespective of whether they are proceeding with a surgical or non-surgical management plan, it is reasonable to conclude that insufficient numbers of subjects were exposed to pre-habilitation.

The combined time delay between injury and surgery and a lack of structured rehabilitation may be reasons explaining the poor pre-operative activity, function and participation seen in this sample. Time without physical activity is known to lead to deconditioning and the effect of injury accelerates this process (Ingersoll et al., 2008) through neuromuscular adaptations (Herrington, 2013; 2001). Time may therefore be a factor that allows greater adaptation that will be discussed in relation to the activity outcomes in more detail later.

Data collection

Data collection was well executed at the intended time intervals with only a few outliers. This was considered a strength of the design and unlike many other studies where there is large variance in the timing of post-operative assessments. The 1 year assessment was carried out very accurately at mean 371 (SD 15) days from surgery.

As anticipated, there were some missing data. Whilst there were a few minor technical errors, this had minimal effect. Therefore the two primary mechanisms were non-attendance and refusal to participate in functional tests. The rate of non-attendance (16.44%) was slightly lower than the 20% reported in previous service reviews. Whilst this suggests that some of the strategies adopted (Hardy et al., 2001; Sharp et al., 2001) were useful, further consideration of patient orientated booking and telephone or SMS reminders (Lin et al., 2014) might improve attendance further. The rate of refusal to participate in functional testing in ACLD subjects (23%) is higher than the 16% reported by Logerstedt et al. (2012), in agreement with the 24% by Roos et al. (2013) and less than the 40% by Button et al. (2014). Logerstedt et al. (2013) conducted a rigorous rehabilitation programme to resolve impairments following injury and greater recovery or practice due to this may therefore explain this difference. The lower refusal rate compared to Button et al. (2014) might be hypothesised to be an indicator of lower levels of risk taking behaviour that is supported by a high fear of reinjury in the Button et al. (2014) ACLD group, however that data is not available in this study to make comparison. Following ACLR, refusal was much less common and reduced over time from surgery. At 1 year there were a few subjects who refused to participate in the squat (n = 4) and hop (n=5) activities, a finding that has not been reported in any other studies. Whilst the study was not set up to examine the reasons for refusal, they were taken as an indication that the subject felt either unable to complete the task, or unwilling to take the risk and therefore an indication of failure to recover.

The missing data rate was sufficiently high to require a statistical solution and following the processes outlined in the methods missing data models were formulated and imputed using expectation maximisation. The imputation models were limited in the number of auxiliary variables that met the r>0.4 standard recommended by Collins et al. (2001). However, at least one variable in each model met the criterion and since the longitudinal nature of the data was preserved in the model the strength of these relationships was maximised.

Question one: Pre-operative status of the ACLD subjects

Within this sample, ACL injury has resulted in significant levels of functional instability, participation restrictions and impairments of knee function. Comparison with the published literature for ACLD subjects prior to ACLR, indicates that this group are towards the lower end of the spectrum of all the measured domains. In combination, the data confirms the expectation that the sample are highly symptomatic non-copers and therefore represent the worse off of ACL injured subjects. These points will now be discussed in further detail.

Functional instability was a considerable problem with 96% of subjects reporting functional instability, whilst 45% occurred during exertion, 51% was during activities of daily living. These high levels of functional instability confirm that subjects were unsuccessful in adapting to maintain functional stability after injury. All of those who were functionally stable had reduced participation and were therefore classified as adaptors. Such high levels of recurrent instability has implications not only for further injury, but also for the development of neuromuscular adaptations and avoidance strategies that occur as a response to try and protect from further episodes of instability, injury or perceived threat of injury (Needle et al., 2014; Hodges and Tucker, 2011). Large and statistically significant reductions in participation were demonstrated in comparison to both retrospective pre-injury (ES = 0.84) and healthy participation (ES = 0.6) levels. The median reduction of 4 points represents a reduction from regular recreational sports to relatively sedentary light labour and walking on uneven ground. The majority of subjects were therefore adapting by reducing participation in response to injury. This prolonged reduction in participation was considered to represent reduced use and therefore had potential consequences for deconditioning of the neuromuscular system (Kaneko et al., 2002; Leiber, 2010). There were just 6 subjects who had maintained pre-injury participation levels, although three of these were in the lower regions of the Tegner scale (<5), three were reporting participation at level 9 which represents competitive sports. These subjects were however reporting instability frequently during exertion and occasionally during ADL and were therefore not making attempts to adapt participation in order to limit instability episodes. Applying this data to the criteria for functional coping; 71 subjects were functionally unstable and therefore classified as non-copers, 3 were functionally stable at a reduced participation level and therefore classified as adaptors, there were no copers.

As hypothesised, there were significant average reductions in knee function measured on the IKDC SKF compared to age and gender matched healthy control subjects. Since no other studies made this comparison, the finding that all subjects reported IKDC SKF below healthy values and an average group reduction of 33% is new information. The group mean IKDC SKF score of 57 (SD = 12) is within the middle range of reports in the literature (see Table 107), suggesting that in terms of knee function this group is perhaps not as worse off as was initially expected. The two samples with better pre-operative IKDC SKF scores, Moksnes and Risberg (2009) and Grindem et al. (2012), differ significantly from this study sample on several important aspects. Both come from systems with early diagnostics and controlled post-injury rehabilitation interventions. This results in a much lower time from injury to surgery (mean 80 and 73 days respectively) than the current sample and is suggested to explain the lower symptomatic state of those samples. This information is unfortunately not available for the Spindler et al. (2011) sample and the lower median score reported here is therefore difficult to compare. From this comparison it is however reasonable to propose that patients in services with greater control over diagnosis and early interventions have higher knee function prior to ACLR.

The Lysholm score also demonstrated limitations in self-reported knee function in this group with a mean score of 61 (SD = 18) which is considered poor (Briggs et al., 2009). Comparison to healthy values was not completed due to the limitations in available data that were discussed in the literature review. Similarly to the IKDC SKF these results are in the mid range reported in the literature (Table 107) for pre-operative ACLD subjects. This result is lower than the values reported by Ahlden et al. (2012), similar to Maletis et al. (2007) and higher than Gobbi et al. (2006). Time from surgery does not seem to be a factor explaining these differences as none of the samples had a mean time to surgery that could be considered to be early and the group with the highest Lysholm (Ahlden et al., 2012) were greater than 1 year with plenty of outliers. Maletis et al. (2007) sample were over 6 months from injury and Gobbi et al. (2006) an average 9 months. These studies do however all come from the Scandinavian system where rehabilitation is often the pathway of choice before considering ACL reconstruction. It is also interesting to note that the pre-operative score is considerably lower than the 87% reported for functional copers at 60 months following injury reported by Muadi et al. (2007), suggesting that the sample in the current study is indeed struggling to cope with ACLD. Differences between study samples such as the coping status, physical conditioning or desire to return to sporting activities may also explain these variances, however these data are not reported and therefore are currently speculative.

Table 107: Studies reporting pre-operative knee function on the IKDC SKF or Lysholm Score

Study	Scale	Mean
Grindem et al., 2012	IKDC SKF	67 (SD = 13)
Ahlden et al., 2012	Lysholm	Male 73 (range 24-100) Female 66 (range 22-99)
Spindler et al., 2011	IKDC SKF	45 (range 34-56)
Moksnes and Risberg, 2009	IKDC SKF	64
Maletis et al., 2007	Lysholm	64
Gobbi et al., 2006	Lysholm	50

Pain was reported by all but 5 subjects; there was a mean score of 28 on VAS and whilst the majority of subjects were classified with mild pain, 14 reported moderate and 11 severe pain. Pain is therefore a common issue in this ACLD sample and for 33% is of a significant intensity. This prolonged impairment of function and presence of pain is suggested to have consequences for neuromuscular adaptations associated with reflex inhibition (Rice and McNair, 2010) and pain adaptations (Hodges and Tucker, 2011). These adaptations are expected to weaken the active stability system with an impact on functional performance.

Explaining deficits

It is proposed that the presence of functional instability in non-copers is explained by a failure in the process of neuromechanical coupling (Needle et al., 2014). There is a failure to adapt or compensate for the increased envelope of passive stability and sensorimotor impairments created by the ACL injury. The mismatch between the capabilities of the passive and active stability mechanisms leads to decoupling and manifests as functional instability and participation restrictions. Impairment of the passive system is worsened by a high rate of meniscal injuries. Impairment of the sensorimotor system (Ingersoll et al., 2008; Ageberg et al., 2002; Solomonow and Krossgaard, 2001; Williams et al., 2001) associated with pain (Tucker and Hodges, 2009; Hodges et al., 2009; Bank et al., 2013) and swelling (Torry et al., 2004) is worsened by prolonged exposure to high symptom levels (Hodges and Tucker, 2011). The highly symptomatic and non coping status of this group suggests they are caught in a vicious cycle (Roland, 1986) in which adaptations to injury and symptoms fail, function becomes increasingly impaired and participation increasingly restricted. The cycle becomes self perpetuating. For these non-coping ACLD subjects the ACLR procedure is seen as the tool to break this cycle, offering improved passive stability and a period during which effective rehabilitation can resolve sensorimotor impairments and a return to pre-injury function and participation.

Both the vicious cycle (Roland, 1986) and pain adaptation theories (Lund et al., 1991) proposed predictable reactions within the neuromuscular system. Muscles were functionally classified and were thought to respond with either spasm or inhibition and create characteristic movement patterns that could be identified through motion analysis. The more recent theoretical contribution of Hodges and Tucker (2011) demonstrated that contemporary evidence does not support this. Rather the evidence suggests that adaptations occur within and between muscles and are therefore individual and task specific. The newer theory suggests that protective motor adaptations occur in an attempt to prevent further pain or instability (Hodges and Tucker, 2011). Whilst these are often effective in the short-term, they may limit the ability to participate and perform at the desired level and will most likely have a negative consequence for the future. It is suggested that in this group, the selected strategies have either not been successful in achieving the short term aim of limiting symptoms, or that the period of success has already given way to the negative long-term consequences of injury and adaptation. In either case a step change created by surgical stabilisation makes sense to break the cycle, change impairments and initiate further rehabilitation to change adaptive strategies. It is not possible to know if post injury rehabilitation could have achieved this step change within this group since it does not appear to have been provided sufficiently. Sensorimotor adaptations were identified as deficits in performance and adaptation in strategy within the three activities, which are now discussed in this context.

Gait

As hypothesised, the ACLD subjects walked with a reduced gait velocity. The difference is however small (ES = .14) representing a 10 % reduction from healthy values.

Importantly, the differences identified in this study were also clinically significant with 52 subjects (70%) walking with a gait velocity slower than healthy. This supports previous suggestions that gait velocity is a “vital sign” for measuring function (Stacy and Lusardi, 2009) and is a powerful tool in defining gait characteristics in knee injured patients (Andriachhi et al., 1977). Given the simplicity with which it can be assessed, it should be considered a powerful clinical assessment tool.

The identified deficit is in agreement with previous reports in ACLD subjects soon after injury (Button et al., 2006; Button et al., 2008, Gao et al., 2010) however it is in contrast with others at 1 year following injury (Button et al., 2005; DeVita et al., 1997; Lewek et al., 2002) and at longer term follow up (von Porat et al., 2006). It seems that this discrepancy is explained by sub-classification on the basis of functional recovery, as demonstrated by Button et al. (2006 and 2008). Functional copers recover gait velocity whilst non-copers, such as those in the current study, do not. The data from the current study therefore adds support to the suggestion that ACLD non-copers can be identified by failure to recover healthy gait velocity (Button et al., 2008). The data also supports the earlier suggestion that the lack of statistical significance attributed to the difference of 13% in gait velocity identified between copers (mean 2.14m/s/leg length) and non-copers (1.87m/s/leg length) by Rudolph et al. (1998) may have been related to insufficient sample size (n = 16).

Interestingly, similar reductions in gait velocity have also been identified in subjects with isolated meniscal tears prior to arthroscopic intervention (Durand et al., 1993; Magyar et al., 2012). It could therefore be suggested that the high rate of meniscal injuries in the current sample may be a further factor contributing to the impaired gait velocity.

There were associated reductions in both cadence and step length. However, as anticipated the covariate effect of gait velocity was strong and these differences were not statistically significant between groups, therefore no specific adaptation other than reduced velocity was identified during gait in ACLD non-copers. Previous suggestions of a specific unilateral adaptation as a result of reduced knee extension at terminal swing or hip advancement angle (Button et al., 2008) in ACLD subjects are not supported by this data. Rather, the bilaterally reduced step length supports Ferber et al. (2004) who demonstrated bilateral accommodations and symmetric performance in ACLD subjects during gait. It is of course possible that the adaptations identified by Button et al. (2008) also affect the non-injured limb as subjects attempt to maintain symmetry and control a limp. In support of this, the data of Button et al. (2008) showed bilateral shortening of step length in ACLD non-copers. Gait has therefore demonstrated bilateral accommodations to unilateral injury, velocity is reduced by reducing cadence and step length on both limbs. Possible mechanisms for such an adaptation are now discussed.

Gait velocity is strongly related to peak knee flexion moments and ground reaction forces (Andriachhi et al., 1977; Kirtley et al., 1985; Zenni and Higginson, 2009) such that slower velocity is associated with lower moments and forces. It is therefore proposed that the reducing gait velocity in the ACLD subjects is a simple attempt to either maintain these forces within healthy levels, or more likely to reduce them to a level that is compatible with stabilising the ACLD knee. The relatively small changes in gait velocity may reflect the low load nature of walking and the relatively small adjustment required. Larger changes would be expected in tasks that require greater loading and knee moments, such as hopping. In support of this suggestion, a recent systematic review from Hart et al. (2010) identified 10 publications that investigated sagittal knee moments in the ACLD population and found a considerable effect of reducing external knee flexion moments. Similar reductions in gait velocity and a link to control of knee joint flexion moments has been reported in overweight and obese subjects (Browning, 2012; Browning and Kram, 2007; Seung-uk et al., 2010). Overweight subjects were able to maintain normal ground reaction forces and sagittal knee moments by reducing gait velocity to from 1.4 to 1.1 m/s (Browning and Kram, 2007). Similar effects have been reported in overweight subjects, where gait velocity is reduced and knee moments controlled within healthy values (Seung-uk et al., 2010). The ACLD subjects in this study were slightly heavier than the control group and it was speculated that this may be due to a rise in body mass due to inactivity following ACL injury. Even with mass included as a covariate gait velocity was reduced in the ACLD subjects, therefore the effect of mass is unlikely to be the defining factor in reducing walking speed in this sample.

Earlier studies have described specific adaptations to gait patterns in ACLD subjects related to reducing external knee flexion moments. Burchuck et al. (1990) described the 'quadriceps avoidance gait' and several authors have subsequently identified reduced quadriceps activity (Bush-Joseph et al., 2001; Patel et al., 2003) and suggested that this is capable of stabilising the ACLD knee (Grood et al., 1984; Hirokawa et al., 1992). Beard et al. (1996) described a contrasting "hamstring facilitation gait" and several authors have subsequently identified increased hamstring activity (Beard et al., 1996; Rudolph et al., 2001; Hurd and Snyder-Mackler, 2007). All of these adapted strategies may manifest as reduced gait velocity as identified in this ACLD sample.

More recently, multiple adaptive strategies have been identified in ACLD subjects, most likely as a function of their symptomatic or coping status. Several studies have proposed increased co-contraction as a mechanism for these adaptations (Roberts et al., 1999; Rudolph et al., 2001; Torry et al., 2004; Hurd and Snyder-Mackler, 2007). Investigations of specificity of muscle action in ACLD non-copers have confirmed global co-contraction of the muscles about the knee (Williams et al., 2003) and an inability to turn off the quadriceps during actions in which it is usually silent (Williams et al., 2004). This presents as a clinically identifiable limb stiffening strategy (Hurd and Snyder-Mackler, 2007) which is consistent with the clinically recognised movement dysfunction of functional rigidity (Elphinstone, 2008) and is a probable mechanism for reducing gait velocity in this ACLD sample.

The kinematics literature also supports the theory of limb stiffening. Most studies indicate that the normal flexion extension pattern of the knee in the gait cycle is maintained (Georgoulis et al., 2003; Hurd et al., 2007) however there is a common theme of reduced knee excursion (Hurd et al., 2007). This is present throughout the gait cycle (Bulgheroni et al., 1997; Knoll et al., 2004; Favre et al., 2006; Hurd et al., 2007; Hartigan et al., 2009), with reductions in the normal peaks of knee extension at initial contact (Rudolph et al., 1998; Button et al., 2008; Risberg et al., 2009), reduced peak knee flexion during loading response (Rudolph et al., 1998; Hurd et al., 2007; Risberg et al., 2009) and reduced knee extension at mid stance (Bulgheroni et al., 1997; Rudolph et al., 1998; Hurd et al., 2007; Risberg et al., 2009; Gao et al., 2010). Reduced knee extension in terminal swing will have an effect of reducing stride length which in the absence of an increase in cadence will result in reduced gait velocity, as was identified in this sample. Limiting ROM during these phases of gait where the knee is functioning as a shock absorber might improve stability (Fuentes et al., 2011).However this has implications for the location of cartilage contact and forces within the knee that have been implicated in the onset and progression of OA in the ACL injured population (Andriachhi et al., 2009; Hall et al., 2012).

Reduced knee excursion has been suggested to provide a stabilising effect on the ACLD knee (Fuentes et al., 2011; Roberts et al., 1999; Beard et al., 1996). Reduced knee flexion during weight acceptance is considered to be a voluntary adaptive strategy, often as a result of weakness of the knee extensor mechanism (Perry and Burnfield, 2010). Compensations may include increased hip extensor activity to retract the thigh or increased soleus activity to prevent tibial advancement and stabilise the knee for mid stance (Perry and Burnfield, 2010), both of which have been demonstrated in the ACLD population (Gardiner et al., 2012; Lindstrom et al., 2010). Although as discussed above, the exact mechanism is debated. It has also been suggested that by maintaining the knee in flexion the destabilising effect of quadriceps contraction would be reduced (Fuentes et al., 2011). Furthermore, in this position of increased flexion, it has been demonstrated that the hamstring muscles would be capable of stabilising the proposed anterior tibial translation (Beard et al., 1996; Li et al., 1999).

Limb stiffening is therefore a recognised strategy adopted during gait in the non-coping ACLD population. The strategy is associated with increased co-contraction around the knee and reduced knee extension at terminal swing and reduced knee flexor moments. Although this was not directly measured this strategy could explain the mean reduction in stride length, cadence and gait velocity in this sample. Variation in adoption of this strategy dependent upon the combined effect of impairments to passive and active stability and abilities of the neuromechanical couple could also explain the variance in gait velocity that was demonstrated. The common theme in all this data is an alteration to the kinematics and kinetics about the knee with increased co-contraction and muscular effort, all of which explain the reduced step length and gait velocity that was demonstrated in this study.

The motor control and learning literature offers an alternative explanation for this strategy and reducing gait velocity which will now be discussed.

Gait is an automatic and repetitive motion that is controlled by central motor commands and pattern generators within the CNS and spinal cord (Shumway-Cook and Wollacott, 2012). Whilst these central generators have built in adaptability to proactively prepare for changes in the environment, there are also mechanisms for adapting gait reactively. Importantly both proactive and reactive mechanisms are highly dependent upon sensory feedback to modify the motor command. Whilst visual feedback is used most often to prepare for changes in the environment such as surface changes and obstacles, somatosensory feedback is also important (Shumway-Cook and Woolacott, 2012). In situations where sensory feedback is eliminated gait patterns slow down and become increasingly rigid and stereotyped (Shumway-Cook and Woolacott, 2012). It will be argued that the proprioceptive deficits that are evident in ACLD subjects (Friden et al., 2001; Roberts et al., 2000; Roberts et al., 2007; Gokeler et al., 2011; Arockiaraj et al., 2013) is sufficient stimulus to lead to this adaptation and explain the reduced gait velocity that has been identified in these non-coping ACLD subjects. Importantly this would also offer a guide to rehabilitation through motor control and learning interventions.

As detailed in the literature review, ACLD subjects are known to have impaired proprioception; although the relationship with functional performance has not been easily understood (Fischer-Rasmussen and Jensen, 2000; Gokeler et al., 2012). Whether this is considered to be a simple factor of deafferentation and alteration in final common input (Johansson, 1991), a more complex model of adaptation in the gamma loop (Proske and Gandevia, 2012) and/or somatosensory cortex (Valeriani et al., 1999), or a combination of all, the net result is the same. A motion system with reduced ability to detect and therefore regulate itself. It seems reasonable therefore to suggest that the central control strategy will respond to an increased unpredictability by changing the proactive control strategy to improve sensitivity of the sensory and motor systems to sense and respond to unexpected perturbations. The result is a system which is prepared for the worse and in a heightened state, a slower and more rigid system as described by Shumway-Cook and Woolacott (2012) and identified within the gait velocity parameter in this sample. Research conducted on the response of gait when stepping on an unanticipated slippery surface has demonstrated that whilst initially subjects use large amplitude saving reactions, with repeated exposure they develop a modified strategy that incorporates proactive gait changes to deal more subtly with the perturbation when it occurs (Bhat et al., 2006; Marigold and Patla, 2002). Cham and Redfern (2002) describe a strategy which uses shorter stride length and reduced loading speed, which is similar to the pattern seen in this current ACLD group. Evidence from the ACLD population is also in support of this suggestion of a more careful movement pattern.

A body of literature utilising non linear dynamics has identified reduced stride to stride variability during gait in ACLD subjects, indicating more rigid and less variable gait patterns. (Stergiou et al, 2004; Leporace et al., 2013). Non-linear dynamics explores the predictability of repetitive elements in the signal and refers to this as local stability. Stergiou et al. (2004) investigated sagittal plane angular displacements at the knee during gait and identified that the local stability was reduced in the injured knee of ACLD subjects when compared to the non-injured knee. This indicates that subjects were less able to respond predictably to local perturbation variations on the ACLD knee in comparison to the non-injured knee. Several other authors have provided data to support this which have been appropriately summarised in a recent systematic review from Leporace et al. (2013). They describe agreement that non-coping ACLD subjects walk with a gait which is more rigid and less variable than healthy subjects. Similar restrictions in gait variability have also been identified in subjects with meniscal tears (Magyar et al., 2012) prior to arthroscopic interventions. Interestingly, Stergiou et al. (2004) found that local stability did not change with gait velocity and they suggest that this indicates an ability to alter the gait pattern in order to maintain local stability at different speeds. They proposed a theoretical model of local stability on a continuum, with complete periodicity at one extreme, and complete randomness at the other. They believe that healthy levels would be somewhere in the middle and that changes in one direction lead to a more rigid and less adaptable system and in the opposite direction a more noisy and unstable system. Importantly, movement away from centre ground in either direction reduces the control over the system and makes functional instability more likely. It is suggested that both ends of this spectrum may result in an identifiable reduction in gait velocity and symptomatic functional instability as identified in this non-coping ACLD sample. These studies together support the proposal that the gait pattern may be slowed by an increase in functional rigidity. Whilst most studies concentrate on lower limb variability during gait, Tzagarakis et al. (2010) have identified the same pattern of rigidity and reduced variability in motion at the trunk during gait in ACLD subjects. This provides further support to the suggestion that whole body mechanics are important considerations when assessing task performance and strategy.

These data are also consistent with the motor learning model of Bernstein (1967). The suggestion would be that despite being an expert at the task (walking) prior to injury, the ACL injury creates a new motor control challenge and therefore the ACLD subject again becomes a novice performer. The Bernstein model suggests that degrees of freedom would therefore be limited to improve control and that performance would be restricted by this. This is in agreement with the summary of data provided by Leporace et al. (2013) and offers a mechanism by which gait velocity may be limited in this ACLD group. This would also suggest that motor learning principles may offer a rehabilitation paradigm for improving gait performance.

There is also a need to consider non-physical reasons for reduced gait velocity. Performance may be suppressed simply by an unwillingness of subjects to perform faster movements in the ACLD state due to a fear of pain or further injury. In that regard this may represent a simple adaptation to avoid harm that is described in the motor control theory of Hodges and Tucker (2011). However, further research will be required to identify the exact underlying mechanism of adaptation.

Biomechanical and motor control theories support the evidence that slower velocity is part of a pattern of functional rigidity that aims to reduce the risk of instability and further injury in ACLD subjects. Unfortunately, in the case of 53% of the subjects in this study who have instability during activities of daily living, the adaptation seems to have failed. These theories and data also support biomechanical mechanisms for the development of OA as a long term complication of adaptation. This adaptation may carry over into other activities and become more apparent as more complex tasks, such as single leg squat and single leg hop increasingly challenge knee stability.

Single leg squat

The SLS has not been well defined as a clinical assessment of motor control and it was therefore possible to adopt and test a novel approach to assess repeated measures. By asking subjects to repeatedly squat on one leg it was anticipated that the number of squats may offer a simple measure that could be used clinically as a milestone for rehabilitation and would also allow the study of variability in SLS performance from a mechanical perspective. By doing this the task was changed from a discrete task to a continuous one. Whilst the healthy subjects performed symmetrically, the ACLD subjects demonstrated significant asymmetry with fewer SLS repetitions on the injured limb. There were also significant reductions in performance on both legs in the ACLD group when compared to healthy, the mean deficit representing a 67% reduction in performance for the injured leg and 52% for the non-injured leg. Importantly the deficit was bilateral in the ACLD group, the performance for the non-injured leg was also significantly less than the healthy group. This will have implications for the use of clinical symmetry scores and comparator groups for recovery that will be discussed further in relation to bilateral deficits in the later themes section.

For the squat depth parameter, the healthy subjects again performed symmetrically, however the ACLD subjects demonstrated asymmetrical squat performance with less knee flexion on the injured limb. Performance in comparison to healthy was however only reduced on the injured limb of ACLD subjects, indicating that in the case of squat depth there was not a bilateral deficit. The mean deficit of 13 % for the injured leg was greater than the 10% deficit in gait velocity and therefore in support of the hypothesised task hierarchy. The mean squat depth on the injured limb (M= 106, SD = 17) and non-injured limb (M =97, SD = 14) again demonstrates intermediate performance in comparison to the few studies that report on single leg squatting in the ACLD population (see Table 108). It should be recalled that the flexion measures in this study are reversed from standard methods, with 180 degrees indicating a fully extended knee; therefore the comparable values are 74 and 83 degrees of knee flexion for the injured and non-injured limb respectively.

Once again this is in the mid range of reports in the literature; however this is accounted for by methodological differences, time from injury and the symptomatic and functional status of the groups. The sample of Yamazaki et al. (2010) are ACLD and awaiting surgery, however they are mean <4 months following injury and have participated in rehabilitation. They were instructed to bend to a position of comfortable balance rather than the maximum knee bend that was instructed in the other studies. The ACLD sample of Button et al. (2014) has substantially less flexion than this sample and the group of Kvist et al. (2005) substantially more. Both studies instructed subjects to squat as deeply as possible, however whilst Button et al. (2014) and the current study did not offer any upper limb support, Kvist et al. (2005) allowed subjects to rest a hand on a stable surface, which might explain the greater flexion demonstrated. Both of these samples also appear to be copers, which might suggest that better performance would be expected. On the other hand limiting knee flexion may be a strategy by which these subjects were able to maintain stability and continue to cope with ACL deficiency. Even with the methodological differences, both groups demonstrated similar restriction in knee flexion during single leg squat when compared to their respective matched healthy control groups, suggesting that limiting knee flexion is a ACLD coping strategy and that this is being adopted within the non-coping ACLD sample in this study.

Table 108: Peak knee flexion (degrees) during single leg squat previously reported in the literature.

Study	Gender	squat depth	
		Injured	Non-injured
Kvist et al., 2005	Both	127 +/- 14	140 +/- 13
Yamazaki et al., 2010	Male	65 +/-19	74 +/-14
	Female	69 +/-13	74 +/-13
Button et al., 2014	Both	63 +/- 9	

The capacity for functional performance between healthy and ACLD subjects is clearly different in both of the single leg squat parameters, suggesting that the task may be useful in differentiating subjects on the basis of activity restrictions. Whilst the squat depth deficit (13%) was in accordance with the proposed task hierarchy, the very large deficit in the squat repetitions (67%) was not. There was a very low correlation between squat depth and squat repetitions, suggesting that these parameters were measuring different constructs. Whilst some subjects had a capacity to perform many deep squats and others performed only a few over a small range of motion, there are also those who perform few deep squats or many shallow ones. There were no identifiable sub-groupings on the scatter plot (Figure 24) that would account for this lack of correlation and performance therefore seems to be highly variable with a mix of strategies. The task requirements for squat repetitions and squat depth are quite different. Squat depth is a discrete task that challenges accurate motor control to produce a single maximal performance. Whereas squat repetitions is a continuous task that requires endurance within the sensorimotor system to maintain control of stability and performance over time.

The large differences between healthy and injured subjects that were identified in squat repetitions suggest that the endurance of the sensorimotor system is not functioning well following injury and is unable to sustain the motor control effort. The finding that a majority of both healthy and ACLD subjects stopped that task due to a loss of balance suggests that impairment in this aspect of motor control is a significant factor. Balance in single limb activities has been highlighted as a significant impairment in the ACLD population (Ageberg et al., 2001, 2005) and this may be the primary cause of reduced squat repetitions in this group. There is of course the need to consider that there may be non-physical reasons for reduced squat repetitions. Performance may be suppressed simply by an unwillingness of subjects to perform repeated movements in the ACLD state due to pain, fear of pain / instability or further injury. A third of the ACLD subjects stopped before losing balance, whilst the reasons for this were not accurately recorded, pain or a lack of desire to continue were often reported. In that regard this may represent a simple adaptation to avoid harm that is described in the motor control theory of Hodges and Tucker (2011).

The differences between healthy and injured subjects that were identified in squat depth suggest that the sensorimotor system is not functioning well following injury and is unable to produce a maximal motor control effort. The ACL is known to be under greatest strain between 30 and 50 degrees of flexion during squatting (Escamilla et al., 2012) and that this reduces with increasing range of knee flexion (Escamilla et al., 2012). On average the ACLD subjects are able to squat well into and above this range and it therefore seems unlikely that passive instability alone can explain the limitation. The active stability system may therefore be the primary limiter. Whilst this data might suggest that the passive stability system is under reducing stress with knee flexion, the active stability system and particularly muscle output are however under increasing stress as knee flexion increases. This may provide an explanation of reducing knee flexion. Deeper squatting requires greater activation of all of the lower limb muscles (Escamilla et al., 2001; Sousa et al., 2007), with squatting to 90 degrees requiring significantly greater activation than both 60 and 40 degrees of knee flexion (Sousa et al., 2007). The quadriceps has been investigated specifically by two studies. Escamilla et al. (2001) demonstrated that rectus femoris activity during squatting peaks between 83 and 95 degrees of knee flexion and Sousa et al. (2007) report increasing demand on the knee extensors above 60 degrees of knee flexion. Sousa et al. (2007)

hypothesise that the greater activation is required to create stronger eccentric contractions to overcome the flexor torque at the ankle, knee and hip joints. The previously presented work on muscle activation failure due to gamma loop dysfunction (Konishi et al., 2002, 2003) and AMI (Rice and McNair, 2010) in ACLD subjects may therefore explain some of the reduced knee flexion angle in single leg squatting as muscles are inhibited from reaching appropriate activation to maintain stability as demand rises.

Sousa et al. (2007) have also highlighted the importance of trunk position during squatting. In their biomechanical analysis a forward trunk lean of 45 degrees was associated with increasing lower limb muscle co activation with reduced rectus femoris and increased biceps femoris activation. Souza et al. (2007) suggested that this is related to the anterior displacement of the COG relative to the BOS and knee joint axis changing the need to control the flexor moments at the lower limb joints (Sousa et al., 2007). Equally changes in length tension of the multi joint muscles crossing the hip may also be a factor. Schoenfeld (2010) speculated that the rectus femoris undergoes significant length change in squatting when the trunk is maintained in an upright stance that would not occur when there is associated forward trunk lean. Whilst trunk lean was not measured during squatting in this study, the 2D TIP methodology could be further developed and applied to the single leg squat data to assess this relationship. This would enable assessment of whether the changes in trunk lean that were identified during hopping also applies to single leg squatting and if so may offer a strategy to consider in rehabilitation.

The co-activation described by Souza et al. (2007) and Escamilla et al. (2001) is one reason why closed chain exercises like the squat and SLS have become popularised in ACL rehabilitation. It is thought to reduce shear forces at the knee and specifically to lower tension in the ACL in knee angles greater than 60 degrees (Sousa et al., 2007), which might be a reasonable protective adaptation in ACLR subjects. This co-contraction is also explained by the adoption of novice motor strategies, with reduced degrees of freedom described by Bernstein (1967), where limb stiffening is used to apply more rigid control over stability and performance. McHugh and Hogan (2004) investigated functional knee stiffness and response to perturbation of flexion at different knee flexion angles. They demonstrated that peak knee stiffness occurred at 70 degrees of knee flexion and reduced in deeper flexion angles. This reduction in functional joint stiffness is likely to be perceived as instability and it therefore seems logical that the motor control system would feel unable to maintain stability beyond angles at which this was sensed and would therefore limit motion. The investigation was limited to open kinetic chain motion on a dynamometer, which limits direct translation to squatting. However, the findings offer a possible explanation for reduced functional stability in deeper squat angles and therefore why a lower peak knee flexion angle might be adopted by ACLD subjects.

More recently Bryanton et al. (2012) have investigated the relationship between squat depth, external load and relative muscle effort. There were significant interaction effects of both load and depth on hip, knee and ankle extensor relative muscle effort. Increasing squat depth was associated with increased hip and knee extensor relative muscle effort but not at the ankle. The authors concluded that training for the knee extensors requires relatively low loads, however a deep squat depth is an important consideration. Squats are generally categorised by depth into squat (<50 degrees) half squats (50 to 100 degrees) and deep squats (>100 degrees) (Schoenfeld, 2010). It is likely that deep squats are avoided in the ACLD population due to associations with high meniscal loads and the associated increased risk of meniscal injury (Schoenfeld, 2010).

There are also considerations within the muscles themselves. The magnitude of force that can be generated by the muscle is dependent on the stimulation, velocity of motion and importantly the length of the muscle (Brughelli and Cronin, 2007; Hahn et al., 2011). This latter phenomenon is the length tension relationship and describes the amount of force that can be produced at a given length of the muscle (Hahn et al., 2011). It is possible to calculate length tension for individual fibres, individual muscles or over individual joints (Brughelli and Cronin, 2007). These all produce very different results that are explained by anatomical and biomechanical variations in the three systems being explored (Brughelli and Cronin, 2007). For the purpose of functional testing, an understanding at the joint level will be most helpful and study of joint torque angle curves will therefore important for further exploring reductions in squat depth.

Whilst no studies directly assessing these factors in single leg squatting were identified, there were useful contributions that can inform this discussion. Isolated quadriceps work has demonstrated that optimal length tension for this group occurs near 60 degrees of knee flexion (Khulig et al., 1987; Pincivero et al., 2004). Hahn et al. (2011 and 2014) have produced a study of multi joint leg extension using the leg press, which is a similar joint motion to single leg squat, although it is considerably more stable with the upper body constrained and weight distributed through more points of contact. It may therefore be simpler in the scheme of functional stability hierarchy that was proposed. They demonstrated that force and torque production was strongly related to joint angle and velocity. In the first experiment they demonstrated that knee joint torque peaked at 50 degrees (+/-9) with the lowest values occurring beyond 90 degrees. This was also supported in the second study and was also found to be related to velocity, with faster movements the optimum angle was increased and muscle lengths were longer. This suggests that force production peaks at 50 degrees of knee flexion and reduces thereafter during whole leg extension tasks and that slower speeds have the effect of moving the peak angle towards extension. Reducing force production is likely to limit a healthy knee in squat depth and further limitations in generating force due to inhibition (Rice and Mc Nair, 2010; Torry et al., 2000; Konishi et al., 2002, 2003) or peripheral muscle adaptations (Leiber, 2010) that have been described are likely to further limit peak knee flexion during single leg squat in highly symptomatic ACLD subjects. In combination these factors can explain the limitation in depth that was demonstrated in this study.

Single leg hop

As hypothesised there were significant and large (ES = 0.65) deficits in hop performance in the ACLD group when compared to healthy values. This was demonstrated despite the concern that the healthy group may represent a conservative estimate of hop distance due to the greater number of females. The mean distance on the injured limb was 1.07m (SD = 0.34), which is lower than all other samples reporting raw scores that were identified in the literature review (Table 9). This difference is not accounted for by methodological differences in measurement, or time from injury and is therefore most likely a reflection of the symptomatic and functional status of the groups. This demonstrates that for the most challenging activity, this sample was particularly poor functioning and was therefore representative of the worse off ACLD subjects.

Table 109: Hop distance (metres) in ACLD subjects as identified in the literature review.

	hop distance (m)	
Study	**Inj**	**Non**
Gustavsson et al., 2006	1.15 +/-.39	1.35 +/-.29
Keays et al., 2003	1.23 +/- .38	1.50 +/-.27
O'Donnell et al., 2006	1.58+/-.12	1.72+/-.18
Ageberg et al., 2008	1.32+/-.05	1.34 +/-.04

Importantly, the deficits in performance from healthy values were identified bilaterally, although they were greater for the injured leg (31%) than the non-injured (19%) leg. The presence of a mean 19% deficit on the uninjured leg is evidence that the non-injured leg does not perform as a healthy limb does and therefore does not support the second assumption of LSI; performance on the contralateral limb is affected in poor functioning ACLD subjects. LSI scores in this group will therefore represent an underestimation of deficits in performance of the injured limb, as the comparator limb is less well functioning than the healthy group. This finding is in agreement with reports from Risberg et al. (2001) that the non-injured limb of ACLD subjects did not recover to healthy values following rehabilitation. Whilst the healthy subjects performed symmetrically the ACLD subjects demonstrated asymmetrical hop performance with less distance on the injured limb. The finding of a mean LSI of 89% is in agreement with other recent reports in the literature (Thomeé et al., 2012; Logerstedt et al., 2013). If the 85% LSI criteria recommended by Barber et al. (1990) are applied to this sample; the group mean LSI of 89% suggests successful restoration of SLHD performance. However at the individual level, only 35 subjects (53%) reach this threshold. The LSI threshold that is selected leads to very different recovery rates ranging from 53% at the lowest LSI standard (85%) to 27% at the highest (95%). This difference in the success rate according to how results are reported highlights the importance of the recommendation of Thomeé et al. (2012) to report individual success at each LSI threshold, rather than at group level. The clinical significance standards for limb symmetry identified from the healthy group data were 94% for partial and 97% for full recovery. This is in agreement with the mean LSI reported in the previously reviewed studies of healthy individuals (Ageberg et al., 1998; Petschnig et al., 1998; van der Hast, 2007; Gokeler et al., 2010). This data suggest that the highest LSI (95%) standard is the most appropriate to reflect healthy symmetry. Importantly, when the clinical significance criteria were applied, only 25% of subjects have normal limb symmetry. This remains an inflated estimate of hop performance as only 14% of subjects were within the clinical significance criteria for hop distance, further highlighting the underestimation of deficits when reporting symmetry rather than healthy comparisons.

In combination this is evidence that there are bilateral restrictions in hop performance in this ACLD sample and that this creates limitations in the interpretation and usefulness of limb symmetry indices. The concern that the use of LSI may mask symmetrically reduced hop performance is supported and LSI should therefore be used with caution. These bilateral effects are a theme throughout the activities and the underlying mechanisms will therefore be further explored and discussed later in section titled 'Bilateral effects'.

The data demonstrates that reducing hop distance is a common strategy adopted in these non-coping ACLD subjects. This may be a simple case of subjects being unwilling to risk performing at a maximal level due to fear of pain, instability or reinjury (Hodges and Tucker, 2011). However, the challenge to knee stability is considerable and therefore this fear is likely to be an appropriate assessment of the reduced ability to control the higher forces involved in the task at both take off and landing.

The take off phase of SLHD has attracted relatively little attention in the literature and no studies assessing take off mechanics in the ACLD population were identified. However, Augustsson et al. (2006) have demonstrated reduced hip and knee joint excursion and power during take-off of a SLHD under conditions of quadriceps fatigue. The reduced distance could therefore be a factor of being incapable of generating sufficient force during takeoff to produce a healthy hop distance. A mild to moderate correlation has been demonstrated between both strength (Fitzgerald et al., 2001; Sekiya, 1998; Petschnig et al., 1998) and power (Andrade et al., 2002; Keays et al., 2003) and hop distance in ACLD subjects. This and the previously described effects of ACL injury on reducing quadriceps activity and strength would support the suggestion that there is insufficient power generated during take-off to produce a healthy hop distance.

Whilst strength measures the quantity of output from the muscle, the quality from a motor control perspective is also important. Assessments of the quality of muscle performance have involved the use of torque curve steadiness (Tsepis et al., 2004; Bryant et al., 2009, 2011; Pua et al., 2014). These studies have identified dyskinesia in the hamstrings and quadriceps of the ACL injured leg. Whilst the exact mechanisms are yet to be defined, they are speculated to be associated with inhibition at the alpha motor neurone and reflex mediated atrophy of type II muscle fibres as a result of pain and swelling following injury (Pua et al., 2014). Reduced torque steadiness has been associated with reduced timed hop performance (Bryant et al., 2009) and in the most recent of these investigations, Pua et al. (2014) demonstrated that isokinetic torque steadiness was an independent predictor of hop distance. The author proposed that greater steadiness in contraction of the muscles improved the control of knee instability and therefore hop performance. It seems that this control of force is important to hop distance, whilst this may be a factor in takeoff it is also and more commonly considered in terms of the ability to safely absorb forces in landing.

There has been more detailed enquiry of the landing phase of SLHD, where there is a need to absorb the considerable forces whilst maintaining knee stability. This phase has been thoroughly explored within this study using the new 2D TIP methodology. Significant differences in landing strategy were identified between Healthy and ACLD subjects. On average, the ACLD subjects landed with a more upright position and with less excursion in both TIP length and angle between IC and PKF, the strategy is therefore less telescopic than healthy individuals. Importantly these differences were apparent on both limbs of the ACLD subjects, again suggesting the presence of bilateral adaptation that is discussed in a later section. The non-injured limb demonstrated the same strategy, although the differences from healthy were smaller.

An important note regarding the methodology is that the ACLD subjects landed with a straighter knee and more upright trunk at IC, neither of which reached statistical significance. However the TIP length parameter at this phase was significantly different between groups. This is further evidence that the TIP model is fulfilling its purpose of measuring whole body strategy, accounting for smaller changes in both kinematic variables which define an altered strategy that is not apparent in the single kinematic parameters alone. This suggests the tool would also be more responsive than the individual kinematic parameters.

This TIP strategy was in direct agreement with Roos et al. (2013) which is the only other study using a comparable TIP model with 3D motion analysis data in the ACLD population. No other study assessing landing strategy on the non-injured limb of ACLD subjects was identified and therefore a bilateral impairment from healthy strategy is a new finding. This strategy would be hypothesised to be associated with reduced knee extensor moments (see Figure 9), as has been described by Roos et al. (2013). The strategy is therefore similar to the knee avoidance strategy or “stiff” landing strategy that has been reported in the literature from different motion laboratories (Gokeler et al., 2010; Laughlin et al., 2011; Risberg et al., 2009; Roos et al., 2013; Button et al., 2014).

Interestingly, this type of strategy has also been linked to increase ACL loading (Laughlin et al., 2010) and has been associated with an increased risk of ACL injury (Pollard et al., 2010). This, in combination with the bilateral effect might suggest that this strategy was adopted prior to injury, rather than an adaptation following injury. This line of reasoning would suggest that these subjects were predisposed to injury due to their selection of motor strategies, as has been demonstrated in female athletes (Griffin et al., 2006; Alentorn-Geli et al., 2009) and confirmed by the sometimes dramatic effects of neuromuscular training programmes on injury prevention (Hewett et al., 2005; Gagnier et al., 2013). However, the subjects in this study demonstrated recovery of this strategy towards healthy after ACLR. This would suggest that this strategy is unlikely to be pre-existing and much more likely a response to ACL injury, this is discussed in later sections in relation to recovery.

Further exploration of the kinematic data revealed that both knee and trunk excursions were significantly reduced in the ACLD group. Mean trunk lean actually reduced between IC and PKF, demonstrating that the trunk moves into a more upright position between phases. This would be consistent with the knee avoidance strategy and compensatory hip and ankle strategies described by both Risberg et al. (2009) and Gokeler et al. (2010). The finding of a more upright trunk is however in contrast to the study of Oberlander et al. (2012) who reported a shorter pendulum, more anterior position of the COG and an increase in trunk lean throughout the landing phase. The use of a fixed hop distance in that study may be a factor influencing this. They fixed distance at 0.75 times height, which is considerably higher than the mean 0.61 times height achieved by the subjects in this study based on self-determination. It might therefore be suggested that subjects were attempting to perform beyond their capabilities and selecting an alternative strategy in order to cope with the higher forces and momentum of the COG motion. Alternatively, this may be a strategy adopted by less severely impaired ACLD subjects. Whilst the symptomatic status of the ACLD group is not reported in the Oberlander et al. (2012) study, all subjects are performing in high level sports suggesting that they are functional copers and therefore less severely impaired. The finding of a group of ACLD subjects who had recovered TIP strategy within healthy values and who had superior performance does however assist with this. The healthy TIP strategy was associated with greater knee flexion excursion than the stiff landing strategy; however there was also an increase in forward trunk lean at both initial contact and throughout the landing phase. This is in direct agreement with the data of Oberlander et al. (2012) and suggests a feed forward compensatory strategy that is used to improve performance. It therefore appears that there are a group of ACLD subjects that choose a deliberate strategy to be successful in improving performance. The finding that only half of this group attended pre-operative rehabilitation suggest that this strategy was not developed as a direct result of rehabilitation intervention and may therefore be learnt through exposure to other tasks.

Risberg et al. (2009) also demonstrated increasing hip flexion during SLHD landing in ACLD subjects following successful rehabilitation intervention. Although their model was based on a lower limb marker set, increasing hip flexion is consistent with forward trunk lean. The adaptation towards increasing hip and trunk flexion in high functioning subjects with ACLD might indicate that this strategy is linked with successful recovery. It could be hypothesised that in terms of achieving the task demands of distance hop whilst maintaining knee stability the forward trunk lean is a positive functional adaptation, whilst upright posture is unsuccessful.

Forward trunk lean leads to a more telescopic strategy, moving the COG forward over the stance limb and bring the ground reaction force vector closer to the knee centre reducing demand on knee extensor moment (Oberlander et al., 2010; Gokeler et al., 2010). In this regard it is consistent with a knee avoidance strategy. The forward trunk lean may also assist in preparing the hamstrings and hip extensors to more readily assist in decelerating the motion during landing. Devita et al. (1998) propose the hip flexion creates a positive change in the functional length tension of the knee flexors and hip extensors. In further support of this Bryant et al. (2009) found that preparatory activity in the hamstrings was associated with greater hop distance and improved control of tibial acceleration during landing in ACLD subjects. Trunk lean and hip flexion may be one adaptation for achieving this. This supports the suggestion that this is a compensation strategy, utilising the hip and trunk to compensate for avoidance of the knee internal extensor moment. Similarly to gait the implications for these strategies on the long term knee health are important to consider. This altered loading would be expected to be sufficient change to stimulate OA as described in the model of Andriachhi et al. (2009).

Question two and three: Recovery following ACLR

There were both statistically and clinically significant improvements in functional stability one year following ACLR. Whilst 46 subjects were considered to be fully recovered, sixteen were partially recovered and 12 had failed to recover. Therefore, whilst ACLR is effective in improving functional stability, recovery is variable. The currently achievable restoration of mechanical integrity and its influence over the passive stability envelope only partially restores the problem of functional instability. It is not possible to comment on passive stability within the sample. Whilst the KT2000 was available at the time of the study conception and for most of the early data collection the instrument became faulty with no facility to have this appropriately remedied and therefore post-operative data was not collected. However, the surgery represents current state of the art and was reasonably controlled across all patients. There is therefore no particular reason to expect significant variance in passive stability beyond that which has already been demonstrated to have a poor relationship with functional stability (Medeni et al., 2014; Patel et al., 2003).

There were statistically and clinically significant increases in participation 1 year following surgery, with the median score restored into the recreational activity section of the Tegner scale. This is in agreement with the reports in the literature of improved participation in ACLR subjects (Ardern et al., 2011, 2012; Grindem et al., 2012). Whilst there were no statistically significant differences between healthy and ACLR there were significant differences in comparison to the retrospective pre-injury measure. On the clinical significance criteria just 18 (24%) subjects returned to their pre-injury participation, leaving 56 (76%) that did not. The previously described potential for recall bias inflating the retrospective measure might suggest that this is a conservative estimate of return to pre-injury participation. This rate of return to pre-injury participation is low in comparison with the 63% reported in the large meta-analysis of Ardern et al. (2011a) and all of the more recent literature reviewed (Ardern et al., 2011b; Brophy et al., 2012; Grindem et al., 2012; Thomeé et al., 2013; McCullough et al., 2012). As previously discussed, the variety of measurement methods and definitions of pre-injury participation make interpretation of these comparisons difficult. Whilst some of the differences could be due to the strict criteria applied to define return to pre-injury sports participation in this study, it seems that a majority may be associated with the highly symptomatic non-coping sample and poor levels of recovery. One year following ACLR there are 20 copers, 26 adaptors and 28 non-copers. Whilst there are a greater number of copers and adaptors, 28 subjects remain with the same functional classification they had prior to surgery.

There were both clinically and statistically significant (P<0.001) improvements in both of the self reported knee function measures over the first year following ACLR. However, despite a large effect size (ES>0.5) the improvement was not sufficient to restore knee function within healthy values with a mean of 8% deficit (ES = 0.55%) remaining on the IKDC SKF. On clinical significance criteria just 19 subjects achieve their age and gender matched healthy value, therefore restoration of healthy knee function is restricted to just 25% of the sample. Recovery is therefore incomplete for a majority of subjects.

The improvement 1 year following ACLR is in agreement with all other identified studies reporting the Lysholm or IKDC SKF (Table 110). The group mean IKDC SKF of 84 is similar to both Grindem et al. (2012) and Moksnes and Risberg (2009), suggesting similar functional recovery. Lentz et al. (2012) divided their cohort on the basis of success in returning to sport, the IKDC scores in the group that were considered less successful were similar to the current study, whilst their successful group who did return to pre-injury sport, had higher IKDC SKF scores (M = 94). Logerstedt et al. (2012) report a mean of 83 at 6 months and recovery to healthy values in 76% of subjects at 1 year post-operative, suggesting better recovery than the current study sample. Whilst some of this large difference in recovery is explained by the use of a more lenient standard for recovery (15^{th} percentile), when this standard was applied to the current study sample recovery remained limited to just 41%. Greater control over the intervention pathway may explain higher levels of recovery seen in the Logerstedt et al. (2012) sample. The pathway included early diagnosis, rehabilitation of impairments, early stratification and both pre and post-operative rehabilitation following the Delaware guidelines for perturbation and strength training. This is in contrast to the later diagnosis and highly variable rehabilitation intervention within the ABUHB service. Recovery is also lower than the 35.5 % of patients above the healthy mean and 28% within 1 SD reported by Harreld et al. (2006), however this difference is explained by this sample being 2 years from surgery.

Importantly, there was just one case of deterioration on the IKDC SKF. The RCI used for the IKDC SKF (7.06) was lower than the MCID reported by Irrgang et al. (2006) of 11.5 points, therefore it is possible that this is a minor underestimation of deterioration. However, the Irrgang et al. (2006) sample examined change after a longer period (mean = 19 months) following a variety of knee surgeries, which given the context dependency of responsiveness measures (Norman et al., 2007; Terwee et al., 2003; Terwee et al., 2010) is likely to affect the subjects interpretation of meaningful change. Since the interest in this study is in terms of both improvement and deterioration, the use of the tighter RCI standard is justified. Therefore, there is evidence that these changes are clinically as well as statistically significant.

In combination this data suggests that whilst the recovery of knee function measured on the IKDC SKF is within the limits of the published literature, they were towards the lower end of functional recovery. Since other studies report higher self reported knee function at 1 year following surgery it seems reasonable to suggest that further improvement within this cohort might be possible. The current cohort has been described as having longstanding, highly symptomatic non-coping status before surgery and will have developed significant neuromuscular adaptations. These factors may limit the recovery of self-reported knee function over the first year following surgery.

Table 110: Studies reporting IKDC SKF (max = 100) or Lysholm knee score (max = 100) at 1 year following ACLR

Study	N	Scale	Mean (SD or range)
Xergia et al., 2013	22	IKDC SKF	72 (89)
Lentz et al., 2012	52 (RTS) 42 (not RTS)	IKDC SKF	94 (6) 78 (16)
Grindem et al., 2012	69	IKDC SKF	85 (12)
Logerstedt et al., 2012	93	IKDC SKF	91 (11)
Moksnes and Risberg, 2009	125	IKDC SKF	87 (2)
Thomeé et al., 2008	38	Lysholm	87 (11)
Maletis et al., 2007	99	Lysholm	95
Gobbi et al., 2006	100	Lysholm	90
Risberg et al., 1999	109	Lysholm	88 (11)

The Lysholm score seemingly highlights the lack of recovery in the current cohort greater than that described by the IKDC SKF; the mean of 79 is lower than all identified reports (Risberg et al., 1999; Gobbi et al., 2006; Maletis et al., 2007; Thomeé et al., 2008) 1 year following ACLR. This may be explained by the specificity of the two scales for the ACL injured population. The Lysholm scale is a disease specific scale, developed specifically for the ACL injured population (Lysholm and Gillquist, 1982), whilst the IKDC SKF is a knee specific scale, developed to assess function in the wider knee injured population (Irrgang et al., 2001). This specificity to the population might be expected to identify differences in function, resulting in the more generic scale (IKDC SKF) underestimating the functional deficit that was identified in the more specific scale (Lysholm).

Whilst pain is statistically significantly improved at the group level, there 10 subjects classified as worse on the clinical significance criteria and only 25% who were fully recovered with a pain free knee. It seems that greater functional stability is most often accompanied by reduction in pain; however a pain free state is rare. There are many possible explanations as to why pain might worsen following ACLR. Consideration needs to be given to complications of surgery that have the potential to lead to pain such as symptoms from the donor site of the autograft (Kartus et al., 2001), arthrofibrosis (Mayr et al., 2004) cyclopse lesion (Delince, 1998) and fibrosis of the anterior interval (Steadman et al., 2008), resection of meniscal tears or the initiation of degenerative disease (Wu et al., 2002) and anterior knee pain (Culvenor et al., 2013; Spicer et al., 2000). However, the important finding is that despite improved function and stability, 14% of subjects reported more pain at 1 year following surgery. This exceeds the MHRA definitions for frequently occurring side effects (>1 in 10 cases) and ongoing pain should therefore be included in the preoperative discussion of potential risks of ACLR (Spicer et al., 2000; Culvenor et al., 2013).

Explaining improvements and incomplete recovery

Prior to surgery non-coping was explained by a decoupling of the stability systems as a result of a failure of an impaired sensorimotor system to adapt to an increased envelope of passive stability. It is now proposed that improvements and incomplete recovery identified in this cohort represents a variable ability of individuals to re-couple these stability systems following surgery and rehabilitation (Needle et al., 2014). Surgical reconstruction restores a degree of mechanical restraint that reduces the envelope of passive stability towards pre-injury levels, whilst simultaneously impairing the active stability system. Sensorimotor impairments, compensations and adaptations that developed and were learnt following injury are altered either as a direct result of rehabilitation or natural recovery. However, incomplete resolution of factors such as pain, swelling and proprioceptive deficits continue to drive adaptations to the coupling process through motor control and motor learning.
The data demonstrates that for 20 subjects classified as copers and 26 adaptors the capabilities of the coupling system are sufficiently improved to regain functional stability at a pre-injury or nearly pre-injury level of participation. It therefore seems that for these subjects ACLR and rehabilitation has been capable of breaking the vicious cycle (Roland, 1986) of symptoms and instability. However for 28 subjects who continue to experience functional instability the systems remain decoupled.
After 12 months of rehabilitation improvements are seen in both the function and participation domains of the ICF. Theoretically these improvements would reduce the need for protective motor adaptations (Hodges and Tucker, 2011) and improvements in performance and alterations in strategy during the activity measures are therefore expected. The activity data will be discussed in the context of improvement and recovery following ACLR and rehabilitation.

Activity

Gait

There were statistically significant increases in gait velocity following ACLR, however recovery was incomplete with a statistically significant deficit from healthy subjects remaining. At an individual level recovery was incomplete with just 43% considered recovered within healthy values. Despite being the least challenging task, gait velocity has proven to be a powerful measure for detecting activity restrictions in this ACLR sample. The use of gait velocity as a "vital sign" for functional recovery (Stacy and Lusardi, 2009) is supported and it is proposed that it may be equally important for classification of recovery following ACLR as has previously been demonstrated in ACLD subjects (Button et al., 2008). Increasing gait velocity was associated with increases in both cadence and step length; however the significant covariate effect of gait velocity meant that these differences were not significant. Again, increases in step length were identified on both limbs, supporting a bilateral improvement following ACLR and adding to the suggestion that the pre-operative findings indicated a bilateral adaptation to injury (Ferber et al., 2004). The data here clearly demonstrate that recovery between individuals is highly variable, that whilst some subjects are able to perform with a healthy gait velocity there are a large number of subjects who cannot. The literature does however support this variable recovery and there is significant evidence that gait remains impaired long after ACLR.

None of the reviewed studies measured gait velocity in the same subjects before and after ACLR and therefore no directly comparable data is available. Whilst Gao et al. (2010) reported reduced gait velocity during the first year following ACLR, all other reviewed studies demonstrated no significant difference from healthy gait velocity at follow up beyond 3 months (DeVita et al., 1997; Bush-Joseph et al., 2001; Lewek et al., 2002; Decker et al., 2004; Webster et al., 2005; Minning et al., 2009). The size of the deficit from healthy identified in this sample was moderate (ES = 0.35) which may be one reason explaining the non-significant differences in other studies with smaller sample sizes which may therefore lack the power to detect this difference. However, the healthy subjects in this study were not high performers and the demonstration of significance is therefore important. The systematic review of Gokeler et al. (2013) focussed on kinetics and kinematics during gait, the synthesis of data from 22 studies clearly demonstrate that abnormalities persist following ACLR. They demonstrate that at 1 year following ACLR there is considerable evidence of reduced lower limb ROM and altered sagittal plane knee moments and that whilst there is a trend for improvement towards healthy values over time, deficits remain detectable up to five years from surgery. Similarly to the ACLD subject's, these deficits are likely to explain the failure to recover gait velocity following ACLR and they are therefore discussed in greater detail.

Increasing gait velocity would be expected to be associated with higher knee moments and ground reaction forces (Andriachhi et al., 1977; Kirtley et al., 1985; Zenni and Higginson, 2009). The systematic review of Hart et al. (2010) demonstrated that on average, ACLR subjects do have greater sagittal knee moments during gait than ACLD deficient subjects. Given that most ACLR subjects in this study were functionally stable during ADL; this suggests that there is improved passive stability and neuromuscular control which is capable of stabilising the knee when subjected to greater forces. Interestingly, knee moments have also been shown to differ between poor and high functioning subjects (Di Stasi et al., 2013) at 6 months following ACLR, adding to the suggestion that gait is useful for monitoring recovery and sub classifying ACLR subjects. Similarly to the ACLD literature, kinetic studies demonstrate adaptations of moments at the hip (Ferber et al., 2002; Kurz et al., 2005; Hall et al., 2012; Webster et al., 2012; Di Stasi et al., 2013).

Co-contraction and limb stiffening was proposed as a mechanism explaining reduced gait velocity prior to surgery. Whilst this remains a theme within the gait kinematics literature in ACLR subjects, there is evidence of reducing limb stiffening and recovery towards healthy values which is proposed as a mechanism enabling an increase in gait velocity. Many studies report reduced knee excursion occurring throughout the gait cycle (Hartigan et al., 2009; Favre et al., 2006; Bulgheroni et al., 1997) or specifically during the stance phase (Bulgheroni et al., 1997; deVita et al., 1998; Ferber et al., 2002,2003; Decker et al., 2004; Knoll et al., 2004; Favre et al. 2006; Gokeler et al., 2003; Gao et al., 2010; Roewer et al., 2011) or at initial contact (Bulgheroni et al., 1997; DeVita et al., 1997; Webster et al., 2012). These changes do however appear to be smaller than in ACLD subjects with several authors describing significant increases in knee excursion in comparison to ACLD subjects (Ferber et al., 2002; DeVita et al., 1997; Bush-Joseph et al., 2001). Three longitudinal studies have considered recovery of knee excursion in relation to healthy values following ACLR. They reported variable recovery and different timescales. DeVita et al. (1998) demonstrated recovery to healthy values by 6 months following surgery, whilst Knoll et al. (2004) reported healthy values at 8 months following surgery and Favre et al. (2006) demonstrated bilateral differences at 12 months following surgery. Similarly to the ACLD situation a reduced knee excursion at initial contact would be expected to reduce stride length and without an increase in cadence could explain why the ACLR subjects are improved but not recovered. Interestingly, these kinematic measures have also been linked to functional status, with high functioning ACLR subjects demonstrating less limb stiffening than poor functioning subjects (Di Stasi et al., 2013).

In the ACLD subjects reduced proprioception was proposed as a mechanism resulting in increased rigidity (Shumway-Cook and Woolacott, 2012). Proprioception is known to improve following ACLR (Angoules et al., 2011; Shidahara et al., 2011; Muaidi et al., 2009) and several studies suggest that proprioception as measured with TTDPM and JPS can be restored to within healthy values following ACLR (Angoules et al., 2011; Risberg et al., 1999). The mechanism for improving proprioception is yet to be fully understood, however is likely to represent a combined effect of improved passive stability, resolution of impairments such as effusion (Torry et al., 2000) and pain (Hodges et al., 2009) and recovery of muscle function and neuromotor control. However it is proposed that improved feedback allows the system to adapt and become more flexible.

EMG studies also demonstrate this recovery with both Knoll et al. (2004) and Bulgheroni et al. (1997) reporting a return to normal quadriceps activity and a reduction in hamstring co-contraction in ACLR subjects that was very similar to healthy values. It was previously discussed that non linear methods had demonstrated a more rigid and less variable gait pattern in ACLD subjects which supported functional rigidity and limb stiffening as a mechanism underlying reducing gait velocity. Similar studies in the ACLR population have demonstrated that ACLR subjects have swung to the opposite side of the spectrum proposed by Stergiou et al. (2004), demonstrating greater variability in knee motion than healthy subjects (Leporace et al., 2013; Tsivgoulis et al., 2011; Moraiti et al., 2010; Kurz et al., 2005). Both Kurz et al. (2005) and Leporace et al. (2013) propose that improved passive stability following ACLR reduces the need for co-contraction, however further impairment of proprioception following surgery alters control of knee motion leading to increased variability in performance. Importantly, this pattern of motion is not within the centre ground of variability that is seen within healthy individuals, and as such represents a more unstable gait that remains less able to respond to perturbation. Again these studies have identified differences in the non-injured limb of ACLR subjects (Moraiti et al., 2010) when compared to healthy values, the authors suggest that this may be an attempt to maintain symmetry or compensate for the ACLR knee, and suggest that this represents a possible mechanism for reinjury and the development of OA. This is consistent with the motor learning model of Bernstein (1967) with ACLR subjects progressing along the spectrum towards advanced performance. However, the kinematic, kinetic and gait variability data all suggest that there are subjects who fail to reach the expert standard and that some subjects remain with reduced degrees of freedom and increased cognitive load (Fitts and Posner, 1967) during gait. Ongoing deficits in proprioception and muscle recruitment are plausible explanations for ongoing limitation of gait velocity. They are intimately linked and are likely to represent the same phenomenon, however further information will be required to identify the way forward.

There has been a suggestion that these alterations in gait may be associated with quadriceps strength. Lewek et al. (2002) divided a small group of ACLR subjects according to quadriceps strength symmetry indices and suggest that there was association between strength and kinematics and kinetics during gait. The differences in kinematics are however very small and represent only a trend, the model also required the addition of a functional scale to reach significance and the relative contribution of strength and function are not reported. Whilst strength may be a factor its importance is not clear and given the low strength requirements of the task its impact ought to be quite small. In contrast, Roewer et al. (2011) have found significant differences in kinematics and kinetics of gait in subjects with normal strength symmetry. Gokeler et al. (2003) have demonstrated that these kinetic and kinematic changes in gait following ACLR are not correlated to either passive instability or quadriceps strength. Rather the authors propose that there is a modification of motor programming that would be consistent with the proposed models of neuromechanical coupling (Needle et al., 2014) and motor adaptation (Hodges and Tucker, 2011). In further support of a neuromechanical adaptation, Hartigan et al. (2008) have demonstrated earlier recovery of gait parameters following ACLR with the use of neuromuscular (perturbation) training techniques when compared to strength training. Although this study is limited by the use of symmetry to define recovery of kinematics.

Finally, there is the need to consider that there may be non physical reasons for reduced gait velocity. Performance may be suppressed simply by an unwillingness of subjects to perform faster movements in the ACLD state due to a fear of pain or further injury. In that regard this may represent a simple adaptation to avoid harm that is described in the motor control theory of Hodges and Tucker (2011). However, further research will be required to identify the exact underlying mechanism of adaptation.

Single leg squat

Following ACLR there was a significant (P<0.001) and large (ES >0.5) increase in the number of squat repetitions performed on both legs that resulted in symmetrical performance between limbs in ACLR subjects. However, ACLR subjects continued to have a significant deficit on the injured leg compared to healthy subjects. There were no previous reports with which to compare the squat repetitions parameter. Interestingly, the number of subjects that stopped the test due to a loss of balance increased to 82%, equivalent to that of the healthy group. Fewer subjects were now stopping the test due to other reasons and there was no association with reported pain. This suggests that there was increased willingness to perform repeated measures to the point of a loss of balance.

There were no significant changes in squat depth on the injured limb and small (ES = 0.16) deteriorations in squat depth on the non-injured limb, with significant asymmetry remaining. The clinical significance criteria indicated that whilst 33 subjects squatted significantly deeper than they did prior to surgery, 20 were unchanged and 21 squatted less deeply. It should be noted that the RCI of 3.3 is slightly larger than the SEM that was calculated from the pilot project, which reassures that this is an appropriate measure for the definition of improvement beyond measurement error. This indicates that the changes were in fact not clinically significant for a majority (55%) of subjects. Only 35% of subjects were considered to have recovered within healthy values.

The mean squat depth on both limbs was not dissimilar to the only two identified studies that report squat depth in the ACLR population (Table 111). When making this comparison it should be highlighted that the ROM measure for squat depth in this study requires subtraction from 180 degrees to be comparable, hence the mean is 77 and 80 degrees on the injured and non-injured limbs respectively. This was greater than both Yamazaki et al.

(2013) and Button et al. (2014), indicating that the subjects in this study were on average squatting with greater knee flexion that either of these other cohorts. This is surprising as both of the other studies had a considerably longer mean time from surgery, with all subjects beyond 12 months, which might suggest they should be further recovered. The Yamazaki et al. (2013) sample were all female which might explain some of the lower squat depth in comparison to the mostly male group in this study, the Button et al. (2014) sample was reasonably comparable in demographic terms and in the methods with which the test was conducted. This suggests that the current group were comparable in recovery and likely to be slightly better than these other studies.

Table 111: Peak knee flexion (degrees) during single leg squat reported in the ACLR literature.

Paper	Population	n	Peak knee flexion (degrees)	
			Injured leg	Non-injured leg
Yamazaki et al., 2013	ACLR Female	28	71 +/-16	73 +/-17
Button et al., 2014	ACLR	24	67 +/-14	

The data demonstrated that there were improvements in squat repetitions but not in squat depth. This suggests that the systems that are involved in these parameters are responding differently following ACLR and rehabilitation and that requires some discussion. Squat depth has previously been considered to be a measure of maximal performance for the functional stability system, requiring control and maintenance of stability as depth increases. Squat repetitions have been considered a measure of the endurance within the functional stability system, maintaining functional stability during a continuous task. Whilst the systems for maximal performance were not improved, a positive change in the endurance of the systems seems to have occurred. The next section will begin by considering the lack of change in the performance, before discussing changes in endurance.

When applying the theory of neuromechanical coupling (Needle et al., 2014) it seems that there is a failure to adapt sufficiently to improve performance from that which was achieved when ACLD. Just as ACL stress and passive instability was reasoned to be unlikely to explain this limitation in the ACLD population, the suggestion that failure to fully restore anterior stability to the knee following ACLR is also unlikely to explain the ongoing limitation in peak knee flexion in single leg squatting in the ACLR subjects.

In the previous discussion of squat depth various theoretical constructs were applied to explain the deficits in peak knee flexion identified in the ACLD subjects. These included an inability to recruit sufficient motor activity due to inhibition (Rice and McNair, 2010, Konishi et al., 2007), dyskinesia (Bryant et al., 2011; Teliandis et al., 2014) and structural changes in the muscle's force producing capabilities (Leiber et al., 2010). When combined with the increasing demand on muscle output with increasing knee flexion angles (Hahn et al., 2011 and 2014) due to length tension changes (Brugheli and Cronin, 2007) and reducing functional stiffness of the knee (McHugh and Hogan, 2004) a restriction in knee flexion was explained. Since no significant difference has been demonstrated between subject before and after ACLR it seems reasonable to suggest that the greater level of activation and force generating capacity of the muscles has not been sufficiently modified by the rehabilitation process. Whether this is due to a lack of sufficient stimulation during the rehabilitation process or persistent inhibition through AMI and gamma loop dysfunction (Konishi et al., 2007) cannot be confirmed. The resulting motion appears to continue to follow the novice motion strategy (Bernstein. 1967) described for ACLD subjects, with limited knee flexion angles. Again the impact of whole body strategy cannot be determined from the currently available data, however it could be suggested that strategy changes following ACLR might be partly responsible for reducing the mechanical efficiency of single leg squatting and that further investigating of this could improve rehabilitation of this task.

As previously mentioned Bryanton et al. (2012) studied squatting in relation to depth and concluded that training for the knee extensors requires relatively low loads, however a deep squat depth is an important consideration. Squats are generally categorised by depth into squat (<50 degrees) half squats (50 to 100 degrees) and deep squats (>100 degrees) (Schoenfeld, 2010). There may be some subjects following ACLR where deep squats are avoided due to concern over meniscal status, particularly if they have had a repair. However it may well be that squat depth is not yet considered an important factor for strength and functional improvements in rehabilitation programmes and a lack of practice into deeper squat angles is a possible explanation for the identified deficits. This is a factor which could be highlighted, not only to improve performance in squatting and other tasks with similar demands, but in quadriceps strength gains. This might reflect the move towards functional training in ACLR rehabilitation and the neglect of strength training that has recently been suggested by Thomeé et al. (2012). Further exploration of the importance of functional recovery will be required before proposing methods by which rehabilitation might target this deficit.

Squat repetitions have previously been described in the context of endurance in the sensorimotor system and altered balance capabilities. It is therefore reasonable to suggest that the improvements can be due to improved endurance of the sensorimotor control mechanisms, enabling a higher number of repetitions to be completed before balance was lost. Whilst balance has been shown to be improved in ACLR subjects when compared to ACLD, a deficit from healthy remains (Shirashi et al., 1996) which may explain this lack of full recovery. More recently, Madhavan and Shields (2011) have demonstrated that ACLR subjects performed poorly in a task that involved perturbations during a tracking motion during a single leg squat task. There was significant overshoot that was correlated to increase in long latency reflex activity, indicating a reduced ability to control the perturbation during the flexion extension movement. The reduced ability to control perturbation in comparison to healthy subjects may explain the reduced repetitions seen in this data, and the increase in the number of subjects stopping the task due to a loss of balance. The reducing number of subjects that stopped the test and rising number who lost balance at a higher number of repetitions, suggests an increasing willingness to perform repeated measures of the SLS. The improved function and reduced pain may be a factor in this, however the lack of full recovery in function and residual pain that has been described may continue to be factors which inhibit subjects from performing more repetitions (Hodges and Tucker, 2012) and explain the deficit from healthy. Improvement in endurance and balance is also expected with rehabilitation programmes which are built on neuromuscular training. According to the American College of Sports Medicine (Ratamess et al., 2009) improved endurance of muscular systems is achieved through high repetition of low load exercise with short rest periods. This is very similar to the recommendations for neuromuscular training and motor learning practices that are often applied in ACLR rehabilitation.

There is of course also the need to consider that there may be non physical reasons for increasing squat repetitions. There could simply be a greater willingness for subjects to perform repeated movements in the ACLR state as there is a reduction in the perceived risk (Hodges and Tucker, 2011) or due to greater motivation to use a knee which has been "fixed" by the surgery. There could also be a simply greater tolerance of repeated motion due to the reduced pain and improved functional stability that has been demonstrated.

Single leg hop

There were statistically significant ($P<0.001$) and moderately sized ($ES = 0.32$) improvements in hop performance on both limbs following ACLR. However, recovery is incomplete since hop distance remains significantly reduced on the injured limb compared to the healthy group. The average deficit is 18% and represents a moderate effect size ($ES=0.38$). Given the conservative nature of the healthy group mean estimate, the true reduction in performance is likely to be even greater. Importantly, the uninjured limb did not show significant differences from healthy; indicating that on average hop distance had recovered to healthy values. This provides some reassurance that the LSI may now be a more valid measure of performance. This suggestion is supported as the LSI also remains significantly reduced in comparison to healthy values and the hop distance on the non-injured limb of those passing the 85% LSI criteria is no longer significantly different from the healthy group. A similar pattern has been described by Lynch et al. (2010); however the information is limited by its presentation as a conference abstract. Contact with the authors has revealed that the study is still in progress and likely to be published in 2015.

The improvement in hop distance is consistent with other longitudinal reports over the first year following ACLR (Thomeé et al., 2012; Logerstedt et al., 2013; Nyberg et al., 2007; Andrade et al., 2002; Keays et al., 2000). Whilst this comparison is limited by the prevalent use of LSI, the group mean hop distance of 127cm is not dissimilar to the reviewed studies (Table 112). There are 2 studies with substantially greater hop distance, Ross et al. (2002) and Matacolla et al. (2002). The Ross et al. (2002) sample were military recruits and both groups were younger, farther from surgery (mean 30 +/- 15 and 18 +/- 10 respectively) and had been discharged from formal rehabilitation. These are all factors which may explain the greater hop distance seen in those studies. The improvement in this study was however better than that reported by Nyberg et al. (2006), as their group did not improve beyond pre-operative performance until after 12 months from surgery. The use of case wise deletion in their study may bias this result. This difference may also be explained as the study was conducted in the early 90’s and the rehabilitation is described as conservative. Whilst the crucial factors affecting rehabilitation have yet to be fully defined, it is clear that early mobilisation (Shelbourne and Klotz, 2006) and the addition of neuromuscular training techniques (Lui-Ambrose et al., 2003; Risberg et al., 2007, Hartigan et al., 2009) have reduced complications and improved outcomes sufficiently to be recommended in ACLR rehabilitation guidelines (van Grinsven et al., 2010; Kruse et al., 2012). The finding of reduced performance on the injured limb is similar to other studies making comparison to healthy groups (Matacolla et al., 2002, Roos et al., 2013; Button et al., 2014). Matacolla et al. (2002) also reported no significant difference between the non-injured limb and matched healthy groups (Matacolla et al., 2002).

Table 112: Studies reporting hop distance (metres) in ACLR subjects

study	mean time from surgery (months)	hop distance (m)	
		injured leg	non-injured leg
Paterno and Greenberger 1996	8 +/-3	1.47 +/- .33	1.68 +/- .25
Gustavson et al., 2006	6	1.28 +/- .28	1.48 +/- .23
Reid et al., 2007	5	1.41 +/-.28	1.60 +/- .26
Ross et al., 2002	>12	1.86 +/-.27	
Matacolla et al., 2002	18 +/- 10	1.74 +/-.28	1.93 +/-.22
Keays et al., 2003	6	1.36 +/- .29	1.55 +/- .23
Ageberg et al., 2008	24 - 60	1.32 +/-.04	1.33+/-.03
Gokeler et al., 2010	6	.94 +/- .19	1.11 +/-.08
Baltaci et al., 2012	18-24	1.33 +/-.25	1.51 +/-.25

Importantly, the improvements were identified bilaterally, although they were marginally smaller for the non-injured leg (ES =0.29) with a mean increase of 14%. The bilateral improvement is reflected in the lack of significant change seen in the limb symmetry index (LSI). This again highlights that symmetry scores have the potential to underestimate effects, in this case a moderate and significant 20% improvement in hop performance would have been considered insignificant on symmetry criteria. The LSI data does however demonstrate improvement when the recommendation of Thomeé et al. (2012) to consider the number of subjects passing each of the symmetry criteria is considered. More people pass each of the LSI criteria at an individual level, however 36% remain below the lower 85%

cut off, indicating that asymmetry even at the lowest standard remains in a large number subjects. The increasing LSI is also reflected in previous studies; Thomeé et al. (2012) report LSI of 94% (+/- 19) and Logerstedt et al. (2013) report 98% (95 – 101). Whilst the group mean improved it should be noted that at the individual level the differences were not so impressive. The number achieving each level of the HOP LSI was increased, however 36% remained below the 85% level and only 49% were above the 90% threshold, an increase of just 6 patients. The importance of using clinical significance criteria is again highlighted as there was a group of 14 subjects whose hop performance deteriorated, 14 remained the same and 46 improved after ACLR.

The group LSI of 91% at 12 months following surgery is lower than that reported in other studies; Thomeé et al. (2012) report LSI of 94% (+/- 19) and Logerstedt et al. (2013) report 98% (95 – 101). Subjects in the Logerstedt et al. (2013) study are exposed to the Delaware pre-operative and post-operative interventions which have previously been described. However, at individual level there are again those that are not performing well, 36 % of subject are not recovered to the 85% LSI and only 49% at 90% LSI. Whilst there are significant average improvements in performance of SLHD one year following ACLR, clinical significance criteria indicate that only 33% perform within healthy range and that 24% perform worse than they did before surgery.

Reduced ability to generate power at take off was proposed as a limiting factor in ACLD subjects and has also been described in ACLR subjects. Orishimo et al. (2010) identified reduced knee excursion and power during take-off of a single leg hop for distance in ACLR subjects, with compensatory increases in power at the hip and ankle. Muscle dyskinesia was proposed as a contributor to reduced force development and an effect on hop performance has been reported in the ACLD population (Pua et al., 2014). Whilst there is no equivalent study making this association in the ACLR population, the presence of ongoing muscle dyskinesia is well evidenced (Bryant et al., 2009; Teliandis et al., 2014). Importantly these changes seem to be independent of mechanical instability; Bryant et al. (2009) found no difference in the torque steadiness curves of ACLD and ACLR subjects and they therefore propose that these changes represent neuromuscular adaptation. Teliandis et al. (2014) confirmed this by demonstrating no correlation between the torque steadiness and anteroposterior instability measured with KT1000. Importantly for explaining recovery, both these groups of ACLR subjects were > 12 months from surgery and therefore support that muscle dyskinesia is one aspect of incomplete recovery that may impact task performance. The ability to control forces in landing was the other major consideration that will now be discussed in relation to the landing strategy data.

Hop strategy

Significant increases in hop performance were accompanied by significant changes in landing strategy. With hop distance included in the covariate analysis, TIP length at IC remained similar; however there was greater excursion before PKF. TIP angle at IC was reduced, increasing the posterior relation of the COG, and angle excursion was increased. Both knee and trunk flexion excursion increased in the ACLR subjects such that subjects were in a more flexed position at PKF. These findings are consistent with an increase in both the telescopic and pendular characteristics of the landing strategy. This strategy is in direct agreement with the data of Roos et al. (2014) and indicates a shift in strategy towards the less stiff strategy of healthy individuals and increased knee loading. The finding of increased trunk lean is in agreement with the report of Oberlander et al. (2013) in ACLR subjects. However, in contrast to these authors the subjects in this study made significant changes to the strategy between ACLD and ACLR.

When compared to healthy individuals different strategies within the ACLR group emerged. At the group level TIP length and angle excursion was greater for the injured side performance; the strategy was now both more telescopic and pendular than the healthy group. Recovery towards healthy values is similar to that reported by Roos et al. (2013), however, they describe ACLR subjects as intermediate between ACLD and healthy. Further investigation of kinematics revealed that this was associated with an increase in trunk lean throughout the landing rather than knee flexion which was not different from the healthy group. Therefore, this appears to represent a further development of the knee avoidance strategy.

Importantly, the non-injured limb performance had a strategy which was much closer to that of the healthy group. Only the TIP length parameter was altered with an increase throughout the landing phase, however all other TIP and kinematic parameters were not significantly different between the groups. This represents recovery of the non-injured limb to healthy and provides evidence that supports the pre-operative strategies as being adaptations to injury rather than pre-existing.

No previous study has assessed sagittal plane kinematics in same subjects before and after ACLR. However, the increase in knee flexion was not unexpected since ACLR subjects have been shown to adopt strategies that are closer to healthy values (Roos et al., 2014). However, studies comparing limbs in ACLR subjects all report reduced knee excursion on the injured limb (Gokeler et al., 2010; Orishimo et al., 2010; Xergia et al., 2013; Button et al., 2014). The sample in this study was considerably larger than previous investigations and they were assessed at a point further in time from surgery and may therefore represent a greater breadth of recovery after ACLR than previous studies. The increase in trunk lean is in agreement with Oberlander et al. (2013) who demonstrated forward trunk lean as a strategy in ACLR subjects that reduces knee extensor moments, but decreases functional stability measured with relations between COM and BOS. However it is in contrast to Roos et al. (2014) who found no significant differences in trunk lean between ACLR and healthy subjects. The differences in 2D and 3D methods may partially explain the difference found in the current study. Also the Roos et al. (2014) group were on average farther from surgery and may therefore be argued to have recovered to a greater extent.

Similarly to the ACLD subjects, a large variation in the strategy parameters was observed. This indicates that there is a wide spectrum of strategies which may be amenable to classification that could prove informative for defining successful and less successful strategies in terms of performance outcomes. Subjects were therefore stratified into three groups on the basis of recovery of TIP strategy parameters, below, within and above the healthy TIP values. Three distinct strategies emerged, the stiff strategy previously discussed in relation to ACLD, a soft strategy previously described in relation to healthy and a new "compliant" strategy. This strategy had greater change in both TIP length and angle and was associated with greater excursion at both the knee and trunk. The most striking difference was an exaggeration of the forward trunk lean at initial contact and increased trunk lean excursion before PKF.

This is equivalent to an exaggerated version of the strategy described by Oberlander et al. (2013). These subjects have a more anterior located COG and increased trunk lean throughout the landing phase, which will bring the ground reaction force closer to the knee and reduce the knee extensor moment (Gokeler et al., 2010), in this regard it is likely to represent knee avoidance. The presence of increased trunk lean at IC in this group supports the suggestion of Oberlander et al. (2013) that this is likely to be a feed forward mechanism. This suggests that it is a planned movement, possibly learnt through experience. Oberlander et al. (2013) have also demonstrated significant correlation between knee extensor strength and the knee extensor moment during landing in subjects who adopted this strategy. It therefore could be suggested these subjects were compensating for knee extensor weakness.

This type of adapted motion has been described within the musculoskeletal rehabilitation literature as “collapse in the same plane” (Elphinstone, 2008). The previously described motor learning theories might start to explain this strategy, with the sensorimotor system selecting a strategy that best achieves the aims of the task, i.e. distance hop. It could be proposed that the system has progressed from a novice strategy, releasing degrees of freedom (Bernstein, 1967), however the dominant release occurs in just the sagittal plane. The accompanying rotations in other planes that might normally assist deceleration are not available and therefore greater sagittal motion is required to effect a safe deceleration. 3D motion analysis would be required to assess this.

A previously unreported association between hop performance and the stratified landing strategy was observed in this group of ACLR subjects. Both the TIP and kinematic parameters were found to be moderately correlated with hop distance ($r = 0.52 – 0.72$) and with performance defined by clinical significance standards (healthy mean +/- 0.5SD). The ACLR subjects who recover hop distance adopted a compliant strategy. Therefore the compliant strategy appears to represent a compensatory mechanism driven by a return to healthy levels of knee bend and excessive forward trunk lean. The strategy is associated with a positive effect on performance and may therefore be appealing for rehabilitation. However the effect on long term knee health remains to be determined. Further investigation of knee loading with this strategy and potential implications for reinjury and longer term knee health will be required. This also leads to questions regarding the use of hop performance as the dominant criteria for rehabilitation progression and return to sport decisions. It has been demonstrated that performance may be regained by adopting an abnormal strategy therefore including strategy measures within rehabilitation seems to be an important element of defining recovery.

The stiff TIP strategy remained in the majority of ACLR subjects (n = 40, 54%), indicating that recovery is limited. The mechanisms behind the strategy are likely to be similar to those discussed in ACLD subjects, with a failure to adapt to the new envelope of passive stability and impaired neuromuscular system. This strategy may have important implications for reinjury. Sheehan et al. (2012) have demonstrated that landing with the COG behind the BOS may be a risk factor for ACL injury and Paterno et al. (2010) identified sagittal plane knee moments in landing as a predictor of reinjury after ACLR. Of the 40 ACLR subjects with this landing strategy at 1 year post-operative, 7 had returned to recreational sports and 15 to competitive sports. These subjects may therefore be at greater risk of reinjury. It is interesting that the group adopting the compliant strategy appear to be doing the opposite, shifting the strategy to move the COG forward. It could be suggested that this is an attempt to reduce the risk of reinjury to the ACL. It could be speculated that this is driven by motor learning during rehabilitation as a strategy that improves the sensation of landing and reduces knee strain. With reinjury rates reported up to 20% (LaBoute et al., 2010) this would be an avenue worthy of further investigation through long term follow up of this cohort. Importantly, there is evidence that landing strategy can be influenced by rehabilitation interventions in healthy subjects. Laughlin et al. (2011) have demonstrated that in healthy subjects verbal cues to land softly with increased knee bend were sufficient to change strategy. Nagano et al. (2011) have described a comprehensive landing training programme including technique and repetition of landing tasks, which was also achieved significant changes in strategy. In the ACLD and ACLR population other factors such as quadriceps strength may also require attention, however investigating the use of this type of rehabilitation intervention to change strategy and increase performance is warranted.

The inclusion of strategy measures seems to be important in defining recovery and could generate novel intervention strategies to improve outcomes and performance. 2D TIP offers a method by which this could be achieved in the clinical setting, however it will require some modification. It may be possible to generate a tablet based application that allows instantaneous capture and analysis of sagittal plane DV and development of the model parameters will be required to produce a user friendly interface that clinicians and patients can understand and use to feedback knowledge of performance.

Emerging themes

Three themes emerged from the data analysis and will now be discussed in relation to available theory:

1. Reduced performance and altered strategy as adaptations in motor control
2. Bilateral effects
3. Hierarchy of activities

Reduced performance and altered strategy as adaptations in motor control

Performance was reduced and strategy altered during all three activities both before and after surgery with limited numbers of subjects achieving recovery. Neuromechanical coupling and motor adaptation theories have been used to explain function and participation deficits and are now summarised in explanation of the limitations and adaptations identified in activity.

Motor adaptation

The model of Hodges and Tucker (2011) can be used to explain the motor adaptations that were identified in this study. Adaptations such as reduced participation, reduced performance, limb stiffening and compliant landing strategies, may be intended to prevent symptoms, protect from further injury or a perceived risk of further injury. However, these strategies were of limited effectiveness, leaving longer term consequences in the form of highly symptomatic functionally instability and non-coping. ACLR provides improved passive stability and during rehabilitation there is an opportunity to generate more useful neuromuscular adaptations to improve functional stability. The highly variable outcome identified in this study suggests that whilst the new adaptations were more successful for some subjects, for others they were not. It is possible that for some the pre-operative sensorimotor adaptations have become somewhat ingrained within the CNS (Valeriani et al., 1999) and that a greater stimulus than current practice offers may be required to bring about positive change. Alternatively, this model might suggest that the ACLR presents a new factor which requires ‘protection’, and therefore a maintenance of protective adaptations that are not conducive to healthy performance or strategy. The growing body of evidence identifying fear of injury as a factor explaining participation restrictions following ACLR would support this suggestion (Kvist et al., 2005; Tripp et al., 2007; Ross, 2010; Ardern et al., 2012). The reduction of performance and adaptation of strategies with feedforward functional rigidity and compliant landing strategy identified in this study can all be explained as protective adaptations via the model of motor adaptation. Importantly, this would provide a direction for developing novel rehabilitation interventions, including motor control and motor learning strategies.

Neuromechanical coupling

Neuromechanical coupling (Needle et al., 2014) describes the ability to co-ordinate the active and passive stability systems through a process of motor learning to maintain functional stability. This model has been used to describe functional coping when the systems are coupled and non-coping when they are decoupled. It is proposed that prior to injury subjects were performing successfully with their individual envelopes of passive and active stability. Injury results in a highly variable impairment of both systems; however for all these non-coping subjects they have become decoupled (Needle et al., 2014) and no longer able to effectively maintain functional stability. Most subjects reduced participation in an attempt to manage the destabilising forces and limit functional instability; however this is most often unsuccessful. Recovery following ACLR is likely to be explained by the variable improvements in both passive and active systems and the ability for the individual to learn to re-couple them (Needle et al., 2014). Recoupling appears to be achieved by the few who are classified as copers, however for the majority the recovery, adaptation and coupling remains insufficient to meet the demands of the activities tested (Needle et al., 2014). This raises the question of whether there was simply too much damage to overcome within either or both systems, or too little ability or opportunity for the sensorimotor system to adapt. The passive, active and motor learning elements of this will be discussed in relation to the data.

Passive stability

Clinical measures of joint laxity during manipulation under anaesthesia clearly demonstrated impaired mechanical restraint at the knee. This was however variable, all three grades of instability (grade I = <5 mm, grade II = <10 mm and grade II = >10mm) were allocated during the Lachmans test, and whilst the majority had rotational instability, 2 subjects did not have a positive pivot shift but were functionally unstable. Passive stability is improved following ACLR (Papangari et al., 2006; Tashiro et al., 2009) and all knees were stable at MUA, immediately after surgery. However, passive stability is known to be of limited correlation to functional performance (Patel et al., 2003; Kocher et al., 2004) and without passive stability data it is not possible to add to this discussion. The surgery applied represents the current state of the art (Voight et al., 2006) and it is therefore assumed that the envelope of passive stability has been improved as far as is currently possible with this technique.

Many other anatomical factors contribute to passive stability. The menisci create a concave tibial socket (Rath and Richmond, 2000) which is particularly important for the lateral compartment where the convex bony architecture is incongruent (Amis et al., 2012). Concavity-compression concept would suggest that reduced concavity in the articulating surfaces following meniscal injury may impair joint stability (Lippitt et al., 1993). Furthermore, the posterior horns of the medial menisci are a stabiliser of anterior translation (Ahn et al., 2012) making their integrity particularly important to the ACLD knee during weight bearing (Shoemaker and Markolf, 1986; Rath and Richmond, 2000; Markolf et al., 2012; Ahn et al., 2012). Whilst the location of tears in the medial meniscus was not specifically measured in this study, the high rate (68%) of meniscal injury in this sample is therefore a probable factor explaining the severity of functional instability symptoms prior to surgery. These factors did not change positively for a majority as only 33% of meniscal injuries were repairable. 31 subjects had meniscal resection, which can further reduce passive stability (Ahn et al., 2011; Markolf et al., 2012) and is associated with worse knee function on the IKDC SKF and shorter hop distance (Wu et al., 2002) and the future development of OA (Jones et al., 2003; Louboutin et al., 2009; Keays et al., 2010; Magnussen et al., 2013). Whilst there was no exhaustive demonstration of correlation between meniscal injury and other outcomes, meniscal injury seems a significant factor in this sample. Tibial slope and femoral condylar geometry have similar influence on passive stability in the weight bearing knee (Hsieh and Walker, 1976; Mclean et al., 2010), however they were not assessed so their contribution cannot be speculated upon.

Whilst these subjects are undoubtedly passively unstable as a result of ACL injury and accompanying meniscal tears, there is evidence that passive stability measures are poorly correlated to functional instability (Patel et al., 2003). Therefore, the role of the active stability system requires close consideration in relation to both the neurological and peripheral tissue mechanisms.

Active stability

Neurological adaptations have been suggested to be driven from deafferentation of ACL receptors, leading to gamma loop dysfunction and reduced afferent activity through the final common input theory (Johansson, 1991). These effects are further amplified when the knee is swollen (Torry et al., 2000) or painful (Tucker and Hodges, 2009; Hodges et al., 2009; Bank et al., 2013) and result in muscle weakness and dyskinesia (Bryant et al., 2011; Teliandis et al., 2014) that is explained by the proposed mechanism of arthrogenic muscle inhibition (Rice and McNair, 2010). Altered motor activity further impacts proprioceptive signals from muscle spindles and interpretation in relation to perceived muscle effort (Proske and Gandevia, 2009 and 2012). The CNS adapts with changes in the cortical areas with which movement is processed (Valeriana et al., 1996, 1999). All of these processes are anticipated to be more significantly impaired in situations of recurrent instability, swelling (Torry et al., 2004) and pain (Hodges et al., 2009) as was the case within this highly symptomatic group of non-copers. Pain and swelling as a result of surgery (Hill and O'Leary, 2013; Heijne et al., 2008) may magnify these adaptations in the early post-operative phase and explain the initial worsening in all parameters in this sample. The removal of autologous hamstring tissue may further affect these processes, leading to short term pain from the donor site and increasing inhibition and weakness of the hamstring muscle group (Hiemstra et al., 2000; Parisaux et al., 2003; Tashiro et al., 2003; Garrandes et al., 2006). However, improvement in these impairments is expected over time, as was evidenced in the improvement in all parameters in the longitudinal data in this study.

Reports of recovery of proprioception are variable, with some authors demonstrating resolution to healthy (Risberg et al., 1999; Angoules et al., 2011; Shidahara et al., 2011) and others identifying long term deficits (Zhou et al., 2008; Anders et al., 2008; Bonfim et al., 2003; Fremerey et al., 2000). Whilst satisfaction has been correlated to deficits in proprioception (Fremerey et al., 2000), recent systematic review has demonstrated that the often small deficits in proprioception have low correlation to function, and may therefore be of limited clinical significance (Gokeler et al., 2010). The mechanism for changing proprioception after ACLR is yet to be fully understood, however it is likely to represent a combined effect of improved passive stability (Isawa et al., 2000; Reider et al., 2003; Muadi et al., 2009) resolution of impairments such as effusion (Torry et al., 2000) and pain (Hodges et al., 2009) and recovery of muscle function and neuromotor control. Interestingly, studies of CNS activity indicate that the changes in cortical activity associated with ACL injury may persist after ACLR (Valeriani et al., 1999; Baumeister et al., 2008), suggesting that proprioceptive and movement processing continue to be affected and may partly explain the altered strategies in this ACLR sample.

Peripheral tissue adaptation occurs in both contractile and non-contractile elements of the musculotendinous systems with reduced use (Leiber, 2010) and following ACL injury (Kaneko et al., 2002). Subjects in this study have significantly reduced participation over a prolonged period between injury and surgery and are therefore considered to be in a state of reduced use. Under these circumstances muscle atrophies, impairing force generation and muscle fibre type converts from slow to fast (Leiber, 2010). Connective tissue becomes less stiff and more elastic (Karpakka et al., 1990; Nakagawa et al., 1989) and as a consequence electromechanical delay is increased (Kaneko et al., 2002). In combination this results in a motor system that is less able to generate high forces and respond quickly to perturbations. Pre-loading of the soft tissue elements with early muscle activation and co-contraction may remove this slack from the system, making it more able to resist load changes (Kaneko et al., 2002). Functional rigidity and a hard landing strategy can therefore be explained as a purposeful change in CNS activity to compensate for weakness, fibre type change and increased electromechanical delay.

The hamstring harvest is perhaps the most obvious muscle tissue change following STG ACLR. Whilst the tendons are known to regenerate and to ultimately have a near normal morphology this process can take up to 2 years (Takeda et al., 2006; Okahashi et al., 2006; Ahlen et al., 2012; Jansen et al., 2011). The hamstring muscles are weak with isokinetic testing (Hiemstra et al., 2000; Parisaux et al., 2003; Tashiro et al., 2003; Gerrandes et al., 2006), and demonstrate increased electromechanical delay (Ristansis et al., 2009, 2011) and dyskinesia (Bryant et al., 2009; Teliandis et al., 2014). Quadriceps function is also often impaired and known to improve but not recover at 1 year following ACLR and rehabilitation, with persistent deficits in muscle atrophy (Krishnan et al., 2011) strength (De Jong et al., 2007; Heimstra et al., 2000), dyskinesia (Bryant et al., 2009; Teliandis et al., 2014) and electromechanical delay (Kaneko et al., 2002). So just as ACLD subjects adopt functional rigidity, it seems reasonable to propose that this will continue in the immediate post-operative period and require significant changes both in motor control and the contractile and non contractile tissues to recover. The length of time and appropriate stimulus for these changes to occur may be a factor in the lack of recovery that was seen 1 year following ACLR.

Motor learning

Motor learning capabilities and therefore the ability to adapt to maintain neuromechanical coupling is expected to be variable between individuals. An association between higher participation and greater neuromuscular abilities (Courtney et al., 2013) might lead to speculation linking recovery and pre-injury participation. However, it is equally possible that these recreationally active individual's were electing to perform below, within or even beyond the natural capabilities of their neuromuscular control system, making participation a poor surrogate measure for neuromuscular capability. Whilst all subjects were likely to be different in this respect before injury, following injury they all presented with an inability to effectively couple the stability systems to maintain functional stability. Symptomatic functional instability (non-coping) is therefore evident, all be it at different participation levels.

The identified reduced performance and altered strategy is in accordance with the 3 stage model of Bernstein (1967) and the comparable model from Fitts and Posner (1967). These authors proposed that motor learning progresses from novice to expert with the sequential gaining of skill and release of DOF. The novice utilises control of DOF with high levels of co-contraction that has become clinically appreciated as functional rigidity (Elphinstone, 2008) and identified as a strategy in both the ACLD and ACLR states. These strategies are effective in completing the task; however they are inefficient and therefore limit performance. The expert however is able to learn to control greater DOF and take advantage of the viscoelastic properties of connective tissues (Roberts and Azizi, 2011; Zelik and Kuo, 2010) to reduce the burden on muscle contraction and increase efficiency and speed, resulting in improved performance. This requires a well functioning neuromuscular system with uninterrupted proprioception and muscle recruitment.

The ACLD subjects were performing more like novices and it is proposed that the ACL injury represents a new and unique challenge to control excessive passive stability at the knee, whilst the sensorimotor system is itself under variable degrees of impairment from the associated consequences. This demands more attention to the control of knee stability and necessitates adaptations throughout the kinetic chain which are seen as whole body adaptations. Improving performance and changing strategy following ACLR and rehabilitation suggests that some subjects have become increasingly proficient in the tasks, moving away from the novice end of the performance spectrum. These changes were demonstrated in all three tasks, however the deeper analysis of strategy in hop creates the clearest explanation. Some subjects have developed a compensation strategy that is associated with improved hop performance; others have regained a healthy strategy, seemingly at the expense of a reduced performance. There are only a few subjects that have regained a healthy strategy and performance that might be considered expert. However, a majority of subjects seem to continue to perform like novices, the hop data demonstrates an ongoing limb stiffening strategy in 55% of subjects.

It was previously suggested that there may simply be too much damage to overcome in this group that has been established as the worst off of the ACLD subjects. The evidence presented so far suggests that this may well be the case. The baseline injury characteristics, functional instability, knee function, and activity performance has been shown to be worse than in most other published samples. Furthermore it has been suggested that neuromuscular adaptations have become more or less ingrained and ineffective over a prolonged period between injury and surgery. It therefore seems appropriate to question how realistic an expectation of recovery to healthy level is. Whilst the surgery is current state of the art (Voight et al., 2006) the data from this study demonstrates that the current service provision does not achieve this aim for the majority of subjects. The recovery models based on neuromechanical coupling, motor adaptation and motor learning provide a plausible explanation for the lack of recovery. Importantly, they also provide a framework within which rehabilitation might be modified in an attempt to improve outcomes.

Therefore the question arises as to whether there was sufficient opportunity for recovery, was rehabilitation optimal and if not how could it be improved?

There are elements of the pathway of care which suggest that the opportunity for recovery was not optimal. Delay in diagnosis means that early rehabilitation to prevent recurrent instability and resolve impairments (pain/swelling) that might limit neuromuscular adaptation is not implemented (Fitzgerald et al., 2001; Logerstedt et al., 2012). Delay has also been linked to increasing rates of meniscal injury that are believed to be acquired during episodes of functional instability (Murrell et al., 2001; Church et al., 2005; Tayton et al., 2009). Rehabilitation after injury and before surgery is limited and whilst content was not specifically measured, subjects who reported having received ACLD rehabilitation were vague about its content or aim, something that should not be possible with a structured programme based upon motor learning and neuromuscular training. However, more structured services with early diagnosis and intervention do have better outcomes (Logerstedt et al., 2012) and therefore changes to the current pathway of care to improve access to diagnostics, early rehabilitation and stratification to surgical and non-surgical pathways is recommended. It seems that more frequent and intense exercise may offer a greater stimulation for adaptation to facilitate recovery. Delivering greater frequency within the existing resources within ABUHB is unlikely and therefore development and investigation of alternative methods of delivery will be required.

Whilst there are guidelines to inform the content of post-operative rehabilitation (Adams et al., 2012; van Grinsven et al., 2010) the optimal methods have yet to be fully developed. There is evidence for various aspects, including neuromuscular and strength training (Risberg et al., 2004; van Grinsven et al., 2010; Lobb et al., 2012; Kruze et al., 2012), which are pragmatically implemented in the ABUHB service by means of a local guideline. The implementation of this will however be dependent upon the knowledge, skills and interest of the clinician as well as the motivation of the patient (Heijne et al., 2008). Whilst the content of ACLR rehabilitation has not been measured, it would appear to be highly variable across the service. The distribution of attendance at rehabilitation and the high non-attendance rate do not reflect a group of subjects who are highly engaged in rehabilitation. Further investigation of the content of rehabilitation using a standardised measure of rehabilitation such as TRAK (Button et al., 2013) would be informative. It seems likely that rehabilitation could improve and the data from this study suggests that a task oriented model built on the principles of motor control and motor learning could be a direction in which to proceed (Benjaminse et al., 2015).

Bilateral effects

Deficits in performance and strategy were identified bilaterally prior to surgery. This is in accordance with a growing body of literature describing bilateral adaptation following ACL (Ageberg et al., 2001; Ferber et al., 2003; Hart et al., 2010; Trullson et al., 2010) and other musculoskeletal injuries (Wikstrom et al., 2010). Improvement also occurred bilaterally in all activities following ACLR, and by 1 year the non-injured limb was not significantly different from healthy during gait and hop. This is in agreement with all other studies that were identified reporting performance of the non-injured limb in similar activities (Logerstedt et al., 2013; Reid et al., 2007; Keays et al., 2000; Gustavsson et al., 2006).

These bilateral deficits have implications for the use of limb symmetry index (LSI) as a performance measure in ACLD subjects, symmetry indices will underestimate the functional impairment as the non-injured leg no longer acts as an appropriate control. The scenario of subjects being classified as recovered on the basis of symmetry when they remain with significant functional impairment is clearly demonstrated in the hop data from this study. Recovery of hop distance to healthy values on the non-injured limb provides some reassurance that limb symmetry may be more appropriate in the ACLR population as on average the comparator limb is considered within healthy values. However, average recovery occurred between 6 and 12 months and some never recovered at 12 months. This has implications for when the non-injured limb can be considered a healthy comparator and LSI an appropriate measure of recovery. This extended period of time to resolve adapted performance on an uninjured leg also suggests that expectations of recovery for the injured leg within a similar time frame are unrealistic. LSI standards have recently been questioned by Thomee et al. (2012) and the data from this study supports their recommendation for reporting across various standards. The identified clinical significance standard in this healthy sample suggests that acceptable LSI should be set at 97%, this is further evidence that the lower standards for LSI are too low and should be reviewed.

The mechanisms for bilateral adaptations have been discussed by Beard et al. (1996). They proposed that bilateral adaptations after unilateral injury suggests that compensatory mechanisms are operating at a higher levels of the CNS, altering central motor command and therefore cross over to affect the non-injured limb. Similar reasoning has been applied by various authors to explain feedforward adaptations during functional tasks including hop for distance (Oberlander et al., 2010; Bryant et al., 2009).

There is growing evidence of CNS adaptation in ACL injured subjects. There are changes within the somatosensory cortex (Valeriani et al., 1996, 1999; Courtney et al., 2005; Kaprelli et al., 2006, 2009). Courtney et al. (2005) demonstrated that changes in cortical somatosensory evoked potentials (SEPs) occurred in ACLD copers and were linked to changes in muscle activity patterns during gait. Kaprelli et al. (2009) used functional MRI to assess brain activity in ACLD subjects in a simple knee extension task. They reported increased activity in the pre-supplementary motor area, indicating that greater planning for even a simple task is required in the ACLD subject. Proprioceptive deficits have been considered a driving force for these adaptations of central motor commands (Kaprelli et al., 2006, 2009) and have been identified in both limbs following ACL injury (Arockiaraj et al., 2013). Cross connections at both the spinal cord and cortical level have been suggested as the pathways by which altered afferent information from the injured knee affects the activity and processing of the gamma loop through the final common input theory (Johansson, 1991). This leads to alterations in the function of muscle spindles on the contralateral leg and diminished proprioception (Roberts et al., 2000) as well as changes in corticomotor excitability (Heroux and Tremblay, 2006). Quadriceps activation has also been shown to be affected bilaterally after ACL injury (Hurley et al., 1992; Urbach et al., 1999; Urbach & Awiszus, 2002; Chmielewski et al., 2004). A recent systematic review identified reduced quadriceps activation on the non-injured side in comparison to control subjects (Hart et al., 2010). Once again the mechanism is thought to relate to gamma loop dysfunction and arthrogenic muscle inhibition that have been previously discussed. Proprioceptive deficits are the common theme throughout these various explanations for CNS adaptation following ACL injury and would appear to be the driving force behind bilateral adaptations.

A lack of investigation of proprioception and muscle activation in the non-injured limb of ACL injured subjects limits further understanding of these explanations. However there has been extensive investigation in subjects with ankle instability (Wikstrom et al., 2010). Whilst the bony and soft tissue anatomy makes the ankle passively more stable, the neuromuscular responses to injury are similar and offer transferrable explanations for functional instability and bilateral deficits (Wikstrom et al., 2010). A recent systematic review from Wikstrom et al. (2010) identified 12 studies and considerable evidence for a bilateral effect on balance in acute but not chronic ankle instability. The bilateral reaction therefore appears to be the same, whilst the ACLD subjects in this study have ongoing or 'chronic' bilateral changes. The ankle is a more passively stable joint and functional recovery from lateral ankle instability is significantly better than that from ACL injury (Wikstrom et al., 2006). This greater level of passive and functional instability in the ACL injured knee could be argued to provide prolonged abnormal sensory input that leads to bilateral accommodation in chronic ACL deficiency and not ankle instability.

An alternative argument is that these bilateral effects are not an adaptation to injury but rather that this was their functional level or preferred strategy prior to injury. There is some evidence that suggests that preferred movement strategies may be a factor for some female athletes who sustain non-contact ACL injuries (Alentorn-Geli et al., 2009; Cameron, 2010; Murphy et al., 2003). For instance, Sheehan et al. (2012) described a high risk landing strategy in healthy female subjects where the trunk fails to progress over the COG at impact, similar to the stiff landing strategy identified in this study. Such patterns of movement have become popular targets for injury prevention programmes and have been shown to be trainable. Several studies report changes to landing strategies and associated reductions in rates of injury following neuromuscular training programmes (Gagnier et al., 2013; Hewett et al., 2005; Mandalbaum et al., 2005). There is a similar suggestion in relation to explaining contralateral injury after ACLR (Sward et al., 2010). Whilst this evidence may relate to a small number of female athletes, the case for bilateral adaptation as a function of the CNS is strong and gaining support. The data from this study provides additional support for bilateral adaptation. Recovery of both performance and strategy parameters on the non-injured limb to healthy values would not be expected if poor performance and altered strategy were pre-existing. This finding of recovery to healthy therefore suggests that for most subjects the non-injured limb was within healthy prior to injury, supporting for the suggestion that the bilateral deficits identified pre-operatively were adaptations to injury rather than pre-existing.

Hierarchical deficits in activity

Task hierarchies have been proposed (Shumway-Cook and Woolacott, 2012) and identified in the ACLR population (Banzer et al., 1999; Ingersoll et al., 2007; Hopper et al., 2008; Button et al., 2013). In agreement with these and the proposed task hierarchy developed for this study, the deficits in the primary activity parameters were hierarchical throughout the longitudinal data. The smallest deficit was in gait, squat depth was intermediate and hop the largest. These data support the proposal that the activity with the fewest challenges to both knee stability and motor control was least impaired, whilst that with the greatest was most impaired.

The relationship in the deficit in squat depth and gait velocity is similar to that reported by Button et al. (2013) when comparing gait and double leg squat. The change of the squat task to a single limb in this study was expected to create a progression in task difficulty, destabilising the task and make deficits larger. The ROM achieved by both healthy and ACLD subjects in single leg squat was approximately 20 degrees less than that in double leg squat reported by Button et al. (2013) however the relative deficit is similar. It seems therefore that progression to a single leg did not have a relative effect on squat depth deficit. Rather, the deficit seems to be in the squat repetitions parameter, with the relative deficit being the greatest of the parameters during the three tasks at both time points. This suggests that the move to a continuous motion with a large knee ROM was the factor that made this task challenging for the ACLD subjects. The majority of subjects at both time points stopped the task due to a loss of balance, suggesting that the dominant mechanism was an impairment of motor control endurance. There were subjects that stopped the task out of choice, however there was no differences in the number of repetitions completed, pain or knee function to account for this, suggesting that this was a conscious choice. Fewer subjects did this after ACLR which suggests increased willingness to push performance through fatigue, uncertainty or fear that might begin to explain these subgroups. It is therefore suggested that reducing repetitions was a protective strategy based upon a fear or expectation of symptoms or harm by continuing to perform maximally. The residual deficit suggests that further advancements could be made with rehabilitation strategies targeted to endurance and repeated performance. The large deficit in this parameter warrants greater exploration to determine the factors that restrict performance and therefore how interventions might be aimed at patient specific factors.

The hierarchy is also explained from a motor learning perspective. Gait is the most frequently performed task, greater exposure and experience to perturbations will have developed a more adaptable motor command on which to learn positive adaptations to ACLD and ACLR. This task will also be practiced as part of a daily routine both following injury and ACLR, the volume of practice would suggest that efficient adaptations that maintain performance are likely to occur. However, SLS and SLHD are infrequently performed and therefore represent relatively novel tasks with limited practice of adaptability within the central motor command. These activities are unlikely to be practiced in daily life, outside of a rehabilitation setting, and with lower volume of practice adaptations are unlikely to be well developed.

From the biomechanical perspective the greater knee moments, speed and acceleration during hop were expected to create greater destabilising forces within the system and therefore a greater demand on control, adaptation or reduction in performance than in the slower, lower load task of gait. This was certainly evident in the hop strategy parameters where reductions in performance were associated with the limb stiffening strategy, whereas better performance was associated with a compliant strategy and large adaptations at the trunk. The task hierarchy continued to be evident in the timing of recovery, which is discussed further in relation to the predictors and clinical milestones in the next section.

Predicting success following ACLR

Application of the clinical significance criteria for success in relation to recovery of each domain to healthy values demonstrated an approximate rule of thirds. There were 26 subjects considered successful, 20 partially successful and 28 who had failed. Furthermore, a hierarchy was observed in the frequency with which each domain was considered fully recovered. Stability was most frequently recovered with reducing frequency in each of participation, function and finally activity measures which were least frequently recovered.

It was not possible to predict successful recovery on the basis of any of the performance parameters. However, performance recovery at one year was predicted by performance of both gait velocity and squat depth in the pre-operative and early post operative period.

Success following ACLR was defined by a functionally stable and symptom free knee which allows return to pre-injury participation, as reported in the consensus statement of Lynch et al. (2015). A single dependent parameter was created using a composite of the functional stability (Lysholm subscale), knee function (IKDC SKF) and participation (Tegner) measures. Success required recovery within the clinical significance criteria established through healthy comparison at the level of half a standard deviation from the mean for each parameter. This method is unique in comparison to all previous studies identifying predictors and associations of successful outcome following ACLR, in two important ways. Firstly, all other studies have used a single dependent parameter (Kim et al., 2005; Laxdal et al., 2005; Heijne et al., 2009; Thomeé et al., 2008; Dunn and Spindler, 2010; Lentz et al., 2012, Ardern et al., 2011; Spindler et al., 2011; Ross et al., 2002; Laxdal et al., 2005; Heijne et al., 2009; Kowulchuk et al., 2009; Eitzen et al., 2009; Kim et al., 2010; Ross et al., 2010; Spindler et al., 2011; Magnussen and Spindler, 2011; Logerstedt et al., 2013) and all have used that in its raw form rather than recovery to healthy. The composite parameter is therefore a very stringent standard both for success and in its definition of recovery to healthy levels. Secondly, previous investigations have concentrated on non-modifiable injury, demographics or lifestyle parameters. Few studies have investigated predictive capabilities of activity performance measures (Logerstedt et al., 2012; Ross et al., 2002, Ross et al., 2010) which are potentially modifiable through rehabilitation and are proposed for use as clinical milestones (Kvist, 2005; Adams et al., 2012; Haines et al., 2013). This study has added to this body of evidence using methods applicable within the clinical environment.

The tasks were selected on the basis of the literature review and further correlation analysis was used in a process of data reduction in order to select the parameters for the regression models. Importantly, none of the activity parameters were sufficiently correlated to the composite success parameter to meet the stepwise regression model entry requirements for predicting success at 1 year following ACLR. This finding was not entirely unexpected and will be discussed. The few studies assessing the predictive capabilities of hop testing are limited to predicting either function or activity parameters, and have shown limited capabilities. Ross et al. (2002, 2010) found that SLHD was a minor predictor adding to the capability of a regression model to predict knee function measured using the knee outcome survey (KOS ADLS and KOS SAS). In the earlier study SLHD LSI added just 4% predictive capability to a model of injury variables (number of injured structures and time from surgery) that already predicted 59% of variance in KOS scores (Ross et al., 2002). In the latter study a model that predicted 60% variance with injury (number of injured structures, repeat surgery, time from surgery) and psychological variables (fear avoidance beliefs - FABQ) was improved by just 1% by addition of the SLHD LSI (Ross et al., 2010). Logerstedt et al. (2012) found that 6 month hop testing was useful for predicting 12 month knee function (IKDC SKF), however the SLHD was the least useful of the hop tests and did not have sufficient discriminatory accuracy to be recommended for use. In a recent and well conducted systematic review of parameters associated with return to pre-injury participation, Czuppon et al. (2014) identified just 4 studies that assessed the association between functional task performance (limb symmetry with hop tests and shuttle runs) and participation outcomes. They found conflicting evidence with 2 studies identifying significant relationships and 2 that did not. They concluded that there is limited evidence of associations between participation outcomes and measures of knee impairment, functional scores and psychological parameters (Czuppon et al., 2014). This lack of association is perhaps not surprising. Noyes et al. (1983) described a group of functional adaptors who they termed ‘knee abusers’. These subjects choose to participate at a high level despite symptoms and poor knee function. It is also known that some subjects who recover good function or activity performance elect not to return to pre-injury participation for various reasons (Reider, 2012). This is also evidenced in the systematic review and meta-analysis performed by Ardern et al. (2011), who report that 90% of subjects recovered functional tasks such as SLHD, however less than 50% returned to sports participation.

Despite the recommendations of several authors regarding the importance of activity measures (Eitzen et al., 2010) this study found no significant association between activity performance parameters and the criterion for success (Lynch et al., 2015). Recovery in the activity domain therefore appears to be largely independent of recovery in the other domains of the ICF. This was not entirely unexpected; the basic premise of the ICF is that the domains are independent and are therefore required to fully explore all aspects of health

(WHO ICF, 2001). It is also clear within the data that there is a hierarchy in the recovery across the domains (Table 113). Success was achieved most often for functional stability, participation and activity parameters were in the middle ground and function was least often restored to healthy age and gender matched levels. This all demonstrated that recovery was variable across the domains and therefore one domain was unlikely to predict success in another or indeed a composite of all.

Table 113: A hierarchy in the recovery of parameters across the ICF.

Domain	Parameter	success (number of subjects)		
		Full	Partial	Fail
Function	Stability	46	16	12
	IKDC SKF	19	19	36
Participation	Tegner	25	26	23
Activity	Gait	32	19	23
	Squat	23	14	37
	Hop	24	9	41

Might it therefore be suggested that activity based measures do not make good clinical milestones or that they are not important for informing rehabilitation progressions? The results of this regression model demonstrated that if the current criteria for success are adopted then the answer would be no. Equally, the data from the literature demonstrated that it is possible to return to pre-injury particiption despite poor knee function and poor activity performance. Therefore if the aim is return to pre-injury participation at all costs then again the answer is no. However, if the desire is to perform well, then these activity measures may be important and become useful clinical milestones for informing rehabilitation. Whilst achieving a desired performance is important, potential association with reinjury (Paterno et al., 2010), the development of pain as a consequence of tissue overload (Elphinstone, 2008) and OA (Andriacchi et al., 2009) makes strategy an important consideration. As an initial step in this process, the prediction of activity performance at 1 year following ACLR was further investigated.

Predicting recovery of activity

In a similar fashion to the success parameter, a composite parameter for recovery of activity performance (gait velocity, squat depth and hop distance) was created on the basis of the clinical significance criteria. Stratification of subjects on this parameter at 1 year following surgery created three groups that seemed to be consistent in their activity performance across the time scale of the study. Those that ended with poor performance started with poor performance and similarly for both partial and complete recovery. This pattern was confirmed in the pre and post-operative predictor models which will be discussed before moving on to explore this phenomenon and make comment on possible causes and implications for practice. Before doing so the relationship between both success and performance recovery with rehabilitation requires some discussion.

Relationship between success and rehabilitation

There was no significant correlation between rehabilitation attendances and both the success or activity recovery parameters and therefore rehabilitation attendance did not meet the entry requirement for any of the regression models. This was not entirely unexpected as there are severe limitations in what the attendance parameter is actually measuring. As previously described the rehabilitation service is built on a model of independent home exercise supplemented with contact sessions with the Physiotherapist for guided progression. The number of attendances required to achieve this will vary between clinicians and patients dependent upon multiple factors such as the level of progress, availability of time and facilities, understanding and confidence with exercise and rehabilitation principles, and motivation. The attendance data does suggest a lack of adherence to the recommendations of the Physiotherapists. There was a high non-attendance (9%) and cancellation (15%) of rehabilitation appointments, together representing nearly a quarter of rehabilitation appointments. Furthermore, a majority of subjects were discharged from formal rehabilitation prior to the 12 months recommended within the rehabilitation guideline; over half were discharged before 7 months, many of these for failure to attend rehabilitation appointments. In combination this data suggests that this group were not completely adherent to the recommendations of their Physiotherapist.

However, rehabilitation attendance is not a measure of rehabilitation content and it is therefore not possible to define the rehabilitation content or experience of the subjects in this study. Content is the primary interest in rehabilitation research, what is done, how much and how often? The complexity of the intervention makes measurement a challenge, however the ability to measure content of rehabilitation has recently been assisted by the development of the TRAK tool (Button et al., 2013), which might be applied in future studies to provide a measure of rehabilitation content. Rehabilitation that is of insufficient intensity, frequency and duration or that lacks specificity to the individual or task is unlikely to be capable of stimulating adaptations beyond natural recovery. This may explain the consistency in the performance parameters across the longitudinal data and the few subjects that managed to change trajectory and improve beyond their original sub-grouping.

Pre-operative predictors

Pre-operative gait velocity and squat depth were significant predictors, together explaining 33% of the variability of performance recovery at 1 year following ACLR. Hop distance did not make the entry requirement for the model. This is a new finding that has not previously been reported. Logerstedt et al. (2012) also found that pre-operative hop testing was not predictive of post-operative outcomes. They suggested that pre-operative functional testing is therefore of limited use in predicting outcome of ACLR. Whilst the SLHD data in this study agrees with this point of view, gait and squat were significant predictors of post-operative activity performance. A hierarchy in the functional tasks has been confirmed and it is the less complex tasks that are acting as the most useful predictors. This was also demonstrated by Button et al. (2005) in the ACLD population, where gait velocity was a significant predictor of future functional stability. The simplest explanation may be that the hop test is simply too complex (Button et al., 2014) and therefore too limited in the ACLD knee to be useful as a predictor of post-operative recovery. However the less challenging tasks of gait and squat seem to allow those with the prospect of good recovery to demonstrate that capability within these tests and reveal a predictive effect. It is therefore speculated that those with the capabilities to recover perform better in the lower demand tasks than those who do not have that capability. This line of reasoning would suggest that the tasks used to assess progress will need to become increasingly complex in the way that they challenge functional knee stability and motor control as recovery progresses following surgery. This concept was used in the data reduction for post-operative predictors.

Post-operative predictors

Once again, the simpler tests in relation to functional stability are those which are of greater predictive value. Hop distance (6 months) did not add to the model; however gait velocity (2 months) and squat depth (3 months) were significant predictors of recovery of activity performance at 1 year following ACLR, accounting for 35% of the variance in outcome.

The selection of time points at which variables were entered into the regression models was structured according to the hierarchy of task complexity and the timescales at which they are recommended within criterion based rehabilitation progressions (Adams et al., 2012). The timescales that were most predictive did fit into the model proposed by Adams et al. (2012) for normal gait at 8 weeks and hop testing between 3 and 6 months post-operative. However, it is interesting that the earlier time points for all three activities fail to meet the requirement for inclusion in the regression model (probability of F at $P>0.10$) whilst the latter time point did. This suggests that functional testing performed too early in the recovery process is not useful for predictive purposes and may relate to the finding that pre-operative hop testing was not a useful predictor.

This has previously been discussed by both Grindem et al. (2012) and Eitzen et al. (2010) who found that a period of initial rehabilitation improved the predictive capabilities of functional testing in ACLD subjects. Grindem et al. (2012) suggested that this is because those with high potential will partially recover during the initial rehabilitation whilst those with low potential will not. This suggests that impairments of structure and function (swelling, pain) created by injury / surgery limit the ability to perform or mask functional performance capabilities in the early phases following injury / surgery. A certain amount of recovery of these factors seems to be required before functional testing is useful (Thomeé et al., 2012). This may be a factor of sufficient time or intervention targeted at resolution of impairments which facilitates a measureable difference in performance. This is supported by the findings of Logerstedt et al. (2013) who demonstrated that there was no predictive capability for hop testing pre-operatively; however there was a strong effect at 6 months post-operatively for predicting IKDC scores at 1 year.

An alternative suggestion is that the subjects need time to become accustomed to the testing procedure in order to perform to the best of their capabilities (Grindem et al., 2012). Whilst the rehabilitation guidelines used in this study take a progressive approach to the practice of walking gait from day one post-op, more complex tasks are not initiated until much later. For instance the rehabilitation guideline in this study does not encourage hop testing prior to 3 months. It is therefore possible that the hop tests at 3 months are the first for some of the subjects. However, all subjects would have been expected to be introduced to hop testing in some form by the 6 month review. This lack of practice may be a factor in the predictive capabilities at 3 months that were improved by 6 months.

The finding that more complex and therefore higher risk activities are not assisting in predicting recovery suggests that these activities need not be tested either pre-operatively or early post-operatively. Furthermore, the high correlation between squat depth and hop distance (r=0.503, P<0.001) suggests that the lower risk test could be used as a surrogate measure, forming part of the risk assessment for completion of SLHD. This will reduce potential risks in clinical practice.

Developing clinical milestones

The identified predictors were further investigated to identify cut off scores at which they may be useful for a clinician to advise a patient on their prognosis in terms of activity recovery. The results suggest pre-operative targets of 1.26 m/s for gait velocity and 105 degrees for squat depth will predict full recovery at 1 year post-operatively with sensitivity of 0.73 and 0.87 and specificity of 0.63 and 0.64 respectively. Post-operatively, gait velocity at 2 months has a cut off of 1.28 m/s (sens 0.73 spec 0.63) and squat depth at 3 months 98 degrees (sens 0.67, spec 0.86), for predicting full recovery at 1 year following surgery. It is proposed that these milestones are used as motivational targets for pre and post-operative rehabilitation programmes and triggers to reassess progress and adjust rehabilitation.
The ROC data for all visits was then used to construct a visual representation of the road to recovery for each of the activity parameters on the basis of complete and partial recovery. Although all the points are not directly predictive of final outcome, the charts offer a visually appealing and simple method to describe and monitor the recovery process. It is anticipated

that the path could be used as motivational milestones and that deviations from a path of recovery could be used to inform rehabilitation progression and planning. This is of course limited to application with subjects similar to those in this study, who are highly symptomatic non-copers with limited recovery following surgery.

It should be noted that the cut-off scores for the full and partial recovery groups are similar in the latter part of rehabilitation for all three activities (>3 months for gait and > 6 months for Squat and hop). This suggests that final recovery has to some degree already been set by those time points and will require some discussion. The data showed very little rehabilitation attendance after 6 months from surgery, if this is also an indicator of rehabilitation activity then it is possible that this lack of progress in the latter period is linked to the lack of rehabilitation progression. There is evidence that suggests that patients lose interest in rehabilitation the further they get from surgery. The study of Heijne et al. (2008) identified 6 months as a common time at which patients assess progress against expectations and often begin to change their goals or give up if expectations are not met. Heijne et al. (2008) recommended the development of realistic recovery targets and goal oriented rehabilitation as a method of avoiding this experience. The data from this study can be used within the service to provide an accurate description of outcomes and to provide a focus for realistic goals and expectations. It could also be suggested that including this information in the pre-habilitation process could highlight these issues when subjects might be more motivated and provide beneficial effects in the latter stages of rehabilitation.

Current performance predicts future performance

As previously described, the data indicates that activity recovery was strongly linked to pre-operative activity and that the groupings were consistent across the timescale of the study. This was identified both at the group and individual level and is clearly demonstrated in Figure 63. There is clear support for the suggestion that 'current performance predicts future performance' in the three activities. Those that fail pre-operatively also fail post-operatively and those that are partially or fully recovered at pre-operatively end in one or either of these camps post-operatively. There are only two subjects who reverse their fortunes in this sample, one who was performing well pre-operatively and failed at 12 months post-operatively and one that failed pre-operatively and achieved full recovery. This is a new finding that has not previously been demonstrated in the published literature and will therefore require discussion.

The first consideration is the standard selected for recovery. It has been proposed that ACLR and rehabilitation aims to restore healthy levels of performance, and clinical significance using matched healthy subjects has therefore been used. However, it is not possible to be sure that all subjects did have this healthy level of performance prior to injury. It may be that they were poor performers prior to injury, who have recovered to their own pre-injury performance, all be it below that of the matched sample. The recovery of performance on the non-injured limb to healthy values makes this unlikely, however it will not be possible to resolve this debate without large scale screening of recreational subjects and follow up of the few that go on to ACL injury. If the healthy standard is accepted then the data demonstrates that current practice is limited in its ability to influence the improvement of performance beyond that which presents before surgery. For those where pre-injury impairment has sunk too low, the current service provision is unable to raise them to a level that is sufficient to constitute recovery to healthy values. It has been argued that recovery is a factor of recoupling of the neuromechanical systems; however the level of recoupling may be limited by several factors. These included characteristics that cannot be changed by either ACLR surgery or rehabilitation. This line of reasoning would include the severity of the injury to the passive stabilisers (Czuppon, 2014) or indeed the persistence of adaptations within the neuromuscular system (Solomonow and Krogsgaard, 2001; Williams et al., 2001; Kaprelli et al., 2009; Leiber, 2010). For instance the high rate of meniscal injury, high frequency of pre-surgery functional instability and prolonged exposure to pain and swelling may have set up persistent changes in tissue or neuromuscular response that will be challenging to overcome. This would fit with the model of spontaneous recovery (Shumway-Cook and Woolacott, 2012) that occurs following injury. However, this sample was exposed to rehabilitation interventions intended to fulfil the forced recovery model (Bach-y-Rita and Balliet, 1987) targeting specific deficits in the hope of facilitating recovery. Following this model it would be suggested that the rehabilitation was insufficient stimulus to promote a change in performance, suggesting that rehabilitation was not optimal. In the rather simple measures of rehabilitation that were included in this study, two deficits are apparent. Firstly, the lack of targeted intervention in the period between injury and surgery and secondly the apparent reduction in rehabilitation activity beyond 6 months from surgery.

Pre-operative rehabilitation

Many of the recent studies assessing recovery after ACLR report the use of early rehabilitation after injury, with the aim of accelerating the resolution of impairments (Fitzgerald et al., 2001; Logerstedt et al., 2013) and allowing for early testing of functional instability and the stratification of subjects to potential coper or non-coper pathways. These pathways have demonstrated effective outcomes, both in allowing subjects to cope with the ACL injury and pursue conservative management and also in outcomes following ACLR (Fitzgerald et al., 2001; Grindem et al., 2012; Logerstedt et al., 2012; Logerstedt et al., 2013). A similarly well-structured service did not exist within ABUHB and is reflected in the low number of subjects (45%) that participated in any form of post-injury/pre-surgery rehabilitation. Shaarani et al. (2012) have recently described pre-habilitation as a void in the care pathway for ACL inured subjects. They highlight the neuromuscular consequences of ACL injury and the potential of rehabilitation to improve or resolve many of these prior to surgical reconstruction. In a subsequent prospective RCT, Shaarani et al. (2014) have demonstrated that a simple 6 week rehabilitation intervention improved functional scores (modified Cincinnati) and activity performance (hop for distance) in comparison to non-intervention. The group that received pre-habilitation were also better on these measures at 12 weeks following surgery, indicating some carry over to post-operative outcomes. Similar evidence of effect of pre-habilitation on hop test results is also available from Logerstedt et al. (2013).

The ability to implement these pathways and post-injury rehabilitation strategies is dependent on early diagnosis, prior to the onset of recurrent instability. It also requires an appreciation of the benefits of early rehabilitation from both surgical and rehabilitation staff and for this to be effectively conveyed to the injured person in order that they might participate fully in this process. Early diagnosis has not proven a simple target to meet. Hartnett (2001) found that despite presentation to medical services within 24 hours of injury, up to three consultations were often required before a diagnosis was made. In this study it resulted in a mean delay to diagnosis of 2 months, however much longer delays in diagnosis (mean 21 months) were reported within the UK NHS by Bollen (1996). It is hoped and expected that this will have improved over the considerable time since this study was conducted. However, even the imperfect tool of time to MRI presented here suggests that there was a considerable delay (mean 10 months) in the diagnosis of ACL injuries within ABUHB. In the period over which this study was conducted, an acute knee clinic has emerged within the knee sub-speciality within ABUHB. The data presented here can act as a benchmark for assessing the impact of this on patient journey and outcome of ACLR. There is agreement that rehabilitation is a viable option for some ACLD subjects (Marx et al., 2003; Goddard and Rees, 2008) and this view is supported by the surgeons in this study. However it seems that these subjects were either not being referred or not engaging with post-injury rehabilitation. How much of this is due to understanding of the benefits of rehabilitation both by surgical and therapy staff is unknown. However, it is clear that a majority of subjects were not engaging in structured rehabilitation that is known to be beneficial to outcome. The previously described work of Heijne et al. (2008), Swirtun et al. (2006) and Thorstensson et al. (2009) highlights the patient's perspective that surgery is often considered the only way of achieving the success that they crave and that rehabilitation is often seen as onerous and ineffective. This suggests that more time should be spent with patients to properly describe the performance effects of disuse and neuromuscular adaptations that have been identified in this study and the possible benefits of appropriate rehabilitation that have been reported elsewhere.

Post-operative rehabilitation

The rehabilitation guideline used within this study was built upon the clinical guideline and systematic review evidence previously presented. Multimodal therapies are recommended to address acute impairments (pain, swelling and motion restriction) alongside a progressive strength and neuromuscular training programme (Risberg et al., 2004, Kruse et al., 2012; Lobb et al., 2012). Neuromuscular training has demonstrated superior outcomes in comparison to strength training in both short (Risberg et al., 2007) and long term follow up (Risberg et al., 2009; Hartigan et al., 2009) and is widely supported within the literature (Ageberg, 2007; Risberg et al., 2004; Kruse et al., 2012; Lobb et al., 2012). This type of training reflects the home-based service applied within this study and will therefore be considered in greater depth.

Zouita Ben Moussa et al. (2009) defined neuromuscular as aiming to "improve muscle activation, increase dynamic joint stability and relearn movement patterns and skills of ADL and sports". Rehabilitation following the principles of neuromuscular training often concentrates on practicing skills related to the performance of movement; however gains in these skills do not necessarily result in improvements in functional performance (Pfeifer and Banzer, 1999; Shumway-Cook and Woolacott, 2012). In order to directly affect functional performance we must also look to the motor control and motor learning literature. Recent publications have highlighted the role for these in musculoskeletal rehabilitation (van Vliet and Heneghan, 2006; Boudreau et al., 2010; Benjaminse and Otten, 2011; Gokeler et al., 2013). Elphinstone (2008) has adopted many of these theories to explain a system for enhancing performance, recovery and injury prevention in the athletic population. That will have familiar language for the MSK therapist and is therefore discussed alongside the less familiar motor control literature.

Motor learning requires a thorough understanding of the task and what defines improved performance (Shumway-Cook and Woolacott, 2012). Feedback is also important to the motor learning process; a subject must understand what improved performance is and have cues which enable learning of progress (Shumway-Cook and Woolacott, 2012; Benjaminse et al., 2015). Within the motor learning literature feedback has been discussed in terms of intrinsic and extrinsic feedback and knowledge of results.

Intrinsic feedback comes from within the individual and includes visual and somatosensory feedback. This is equivalent to the idea of 'feeling the performance' proposed by Elphinstone (2008) and the idea that a subject can feel when a task is performed well and badly. Recent advancements in the understanding of proprioception suggests that it is the difference between intended and actual motion which leads to conscious proprioception (Proske and Gandevia, 2009; 2012; Wolpert et al., 2011). It could be suggested that the feeling of a "good" movement is therefore a match with the intention and that "poor" movement which does not fit the intention feels odd and uncomfortable. Focussing on the feeling of the movement therefore becomes important in rehabilitation (Elphinstone, 2008). In situations such as ACL injury, it is possible that altered proprioception interferes with this process and distorts both the intended motion and the feedback of actual motion.

Extrinsic feedback comes from external sources and in the case of rehabilitation most often via a therapist in terms of verbal cues. Knowledge of results relates to the success in achieving the task aims (Schmidt and Lee, 2005), for the tasks in this study this would be healthy gait velocity, squat depth and hop distance. This is in contrast to knowledge of performance, which is related to the strategy that was selected to achieve the task aims

(Shumway-Cook and Woolacott, 2012). This is often referred to as ‘form’ in clinical language (Elphinstone et al., 2008) and is represented by landing strategy in this study. Knowledge of results can be simply measured in the clinical environment using tape measures and stopwatches, whilst knowledge of performance requires mirrors or the 2D DV system used within this study. Whilst it is possible to include all of these in rehabilitation practice they are not features that are within the current ABUHB ACLR rehabilitation guidelines and therefore may not have been included in rehabilitation programmes and provide an avenue to investigate development of current rehabilitation provision.

Task oriented rehabilitation strategies in these ACLR subjects might be as simple as training faster gait with greater step length and increased cadence. This is supported by the work of Decker et al. (2004) who have demonstrated restoration of temporospatial gait parameters in the ACLR population following training on the basis of individualised cadence. Similar rehabilitation strategies could be applied to target increased knee flexion in single leg squat and incremental increases in hop for distance. Landing strategy might be trained to change limb stiffening. McNair et al. (2000) have used verbal cues focussed on knee kinematics and the sound produced on landing to successfully influence landing strategy. Others have used video feedback of performance and demonstrated ability to soften landing strategy (Onate et al., 2001; Onate et al., 2005). It would be possible to provide sagittal plane feedback using the 2D digital video system or even a real time calculation of 2D TIP strategy parameters to provide depth to the feedback of knowledge of performance. This type of augmented feedback has demonstrated greater changes in landing strategy than internal or external cues alone (Onate et al., 2001). Interestingly, there is also an increasing body of research supporting the use of visual feedback (Dyad training) using expert task performance (Benjaminse et al., 2015; Wolpert et al., 2011). These strategies are believed to work through imitation and activation of mirror neurones that link visual input and motor output (Benjaminse et al., 2015; Wolpert et al., 2011).

Benjaminse et al. (2015) have recently reviewed the motor learning literature and provide a perspective on feedback strategies that might be effective in relation to ACL injury prevention. Although it is suggested that this is equally applicable to rehabilitation of ACLD and ALCR subjects. They present a convincing argument that external cues provide better changes in strategy with better retention and transfer than is achieved with internal cues. Therefore the recent trend in rehabilitation to internalise feedback using cues such as

“knees over toes” may be limiting the performance and learning of automatic skills. The paper provides a comprehensive summary of the differences in the approach that could be very simply adopted within ACLR rehabilitation practice within ABUHB.
Volume of practice is also important to the motor learning process as has been described in the Fitts and Posner (1967) model of motor learning. Schmidt and Lee (2005) have described this as a power law of practice where rate of improvement follows a logarithmic progression. This means that early in the practice of a task improvements are large, however smaller improvements are seen with greater levels of practice required as performance improves. The Fitts and Posner (1967) model and the Schmidt and lee (2005) law would suggest that those subjects with the lowest performance will see greater gains with the same amount of practice that those with relatively higher performance, and it should therefore be relatively more simple for those at the lower end of the spectrum to progress up than those in the middle or higher ground. This was not apparent in the study data, suggesting that practice volume may not have been sufficient to provide a stimulus for change. These theories also suggest that rehabilitation volume will need to increase as task performance progresses. With the rehabilitation attendance that has been described in this study it seems unlikely that practice volume and intensity was sufficient for a majority of the subjects and may explain some of the lack of recovery.

It seems that current rehabilitation practice is able to addresses some deficits in performance and strategy, however it is an insufficient stimulus to achieve full recovery for a majority of subjects. Current theory suggests that adaptations in performance and strategy may be better achieved through the adoption of rehabilitation methods based upon the theories of motor learning. Increasing intensity and frequency of practice and including external cues and feedback through knowledge of results and performance will be areas for development. Including these with strategies that enable subjects to access to these resources on a regular basis within the often complex rehabilitation environment will be essential to their success.

Conclusion

There is an expectation from ACL injured subjects and the international clinical community that ACLR and rehabilitation will facilitate a return to pre-injury knee function, activity performance and participation. Whilst few studies use appropriate methods to adequately assess this expectation of recovery, the reality seems to be a highly variable and often incomplete recovery that is difficult to predict. This study has provided a unique, clinic based longitudinal analysis using multiple outcome measures and clinical significance methods which directly assesses recovery against this standard and identifies modifiable predictors which may guide rehabilitation. The methods for data collection, processing and analysis were robust. A comprehensive systematic review (Letchford et al., 2012) and comparative analysis of measurement properties (Letchford et al., 2015) has enabled selection of an appropriate participation PROM. A novel method for the evaluation of landing strategies has been developed and evaluated for measurement properties (Letchford et al., 2014).

The large sample (n=74) represented a chronically injured, highly symptomatic, non-coping ACLD population with a high rate of meniscal injuries. ACLD subjects had large deficits in all outcomes, however despite statistically and clinically significant improvements 1 year following ACLR, they often did not fully recover. The null hypothesis for research questions one, two and three were therefore not rejected. Pre-operative deficits were larger than other studies and are explained by the highly symptomatic non-coping status of subjects. There were greater frequency of meniscal injuries and evidence of sensorimotor adaptation in response to prolonged exposure to symptoms over a protracted time from injury surgery. Improvements are in accordance with the literature; however the novel consideration of recovery to healthy levels using clinical significance methods is new information. There was an approximate rule of thirds as roughly equal proportions of subjects became classified as copers, adaptors or remained non-copers, demonstrating that recovery is incomplete for a majority. Interestingly, deficits and recovery were hierarchical across the ICF domains with greater deficits in the knee function and activity performance measures than functional stability and participation; suggesting that greater attention to the rehabilitation of impairments and limitations is required.

The activity measures demonstrated significant deficits in performance such that ACLD subjects walked more slowly, squatted less deeply and hopped less far than healthy subjects. On average deficits remained following ACLR and a minority of subject's recovered healthy performance. The hierarchical nature of deficits across the tasks supports the proposed taxonomy of tasks and provides a guide for rehabilitation progression in this population. Further development of task oriented rehabilitation progressions can be built on the application of these biomechanical and motor control / learning theories. There were also significant alterations in strategy parameters. A stiff strategy was identified in ACLD hop landings, which was maintained by many following ACLR. Few subjects returned to a healthy landing strategy following ACLR, however a number subjects compensated by using a compliant landing strategy that was associated with improved performance. Interestingly, the most significant adaptation to strategy occurred in the trunk lean parameter, suggesting that whole body adaptation is used to control dynamic knee stability in hop landing. Whilst this may be seen as a positive compensation for performance recovery, the long term consequences of such a strategy for reinjury and the development of OA require investigation.

Non-coping and the associated deficits and adaptations have been described as decoupling of the active and passive stability systems following injury. ACLR and rehabilitation is sufficient stimulus to re-couple the stability systems for those classified as copers after ACLR. However, for the adapters and non copers, the recoupling is insufficient to return them to healthy status. It seems therefore that either the damage is too severe or that current practice does not provide sufficient stimulus for the majority of subjects to succeed. Well documented sensorimotor adaptations following injury are known to impair the dynamic knee stability system at multiple levels of motor control. Targeting these adaptations with rehabilitation based upon motor learning and control theories, from the early period after injury and following ACLR may limit deficits in dynamic stability and enable recoupling.

Importantly, both performance and strategy effects were identified bilaterally. There was evidence of bilateral adaptation following unilateral injury, which is explained by various sensorimotor adaptations at multiple levels of the peripheral and central nervous system. Whilst there was on average recovery for the non-injured leg, the amount and timing of recovery was highly variable across individuals. This indicates that there are significant limitations in the use of limb symmetry indices as a primary measure of performance, particularly in the highly symptomatic ACLD population. Raw performance and healthy comparisons are therefore preferred.

Success was defined by the use of a novel composite parameter that reflects patient and professional expectations. None of the outcome measures was able to predict success, reinforcing the need to consider all domains of the WHO ICF when defining recovery. A composite parameter for successful recovery of activity performance indicated that recovery was predictable on the basis of both pre and early post-operative performance in the simpler tasks of gait velocity and squat depth. These parameters have been developed into clinical milestones that might be used to advise on prognosis, trigger re-evaluation of expectations or modifications to rehabilitation interventions.

Several recommendations have been made. The pathway from injury to surgery could be improved with the aim of reducing pre-operative deficits. This would include early diagnosis and rehabilitation intervention with screening to fast track non-copers to ACLR at the right time for the individual. The recovery data should be used during pre-operative counselling to provide a realistic expectation of outcomes and to plan rehabilitation schedules. The clinical milestones for gait velocity and squat depth can be used to inform these schedules and progressions throughout the rehabilitation period. Development of novel ACLD and ACLR rehabilitation strategies using motor learning and motor control theories is also recommended. These should include the use of high volume practice, external cues and real time feedback using knowledge of results and knowledge of performance. The DV methods applied in this study should be further developed to a tablet or phone application to allow easy access to real time feedback in a variety of rehabilitation settings. Further investigation of the identified landing strategies is required to establish the effects on joint loading and longer term implications.

This study of functional recovery following ACLR has provided a unique insight into recovery in this sample. Highly symptomatic non-coping ACLD subjects achieved significant improvements but most often incomplete recovery at 1 year following ACLR. It seems that changes to the intervention pathway and rehabilitation interventions have the potential to improve on this situation. Early diagnostics and classification can put patients on the right pathway and limit unhelpful adaptations, whilst adoption of novel motor control and learning rehabilitation strategies may enable useful adaptations that promote recovery. Further development of these methods and modes of delivery to suit the modern health service are now required.

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Appendices

Appendix 1: ABUHB ACLR rehabilitation guideline

Anterior Cruciate Ligament Reconstruction (ACLR)
Autologous Hamstring Graft
Rehabilitation Guidance

This guidance is to be used by physiotherapists when developing a rehabilitation programme for ACLR patients. The programme should be tailored to the individual capabilities and needs of the patient and progressed when appropriate. ACL is commonly accompanied by other procedures such as meniscal repair which should also be considered – so check the operation notes.

Patients in South Gwent are followed up in the physiotherapy review clinic in Physiotherapy at the Royal Gwent Hospital. You will be asked to contribute to this process by completing patient reported outcomes at designated times. Any problems or complications can be discussed with the ACLR review clinic (RGH Extension 4417).

TIME	AIMS	PRECAUTIONS	SUGGESTIONS
DAY 1 TO 2 WEEKS	Protect graft and donor site Monitor wounds Pain relief Reduce swelling Regain ROM Regain muscle activity Normalise gait	Closed kinetic chain (CKC) quadriceps exercises produce less anterior tibial shear and therefore have a lower risk of graft disruption or stretching. The graft is vulnerable to rotation and acceleration / deceleration tasks.	FWB as comfort allows Cryocuff / RICE / PROM / AROM and AAROM exercises Active exercise to activate muscles Cycling when have appropriate range
At 2 weeks aim for: FWB, full extension ROM and active SLR with no lag.			
2 TO 6 WEEKS	Regain FROM Increase muscle strength, power and co-ordination	CKC quadriceps exercise produce less anterior tibial shear	Stretch flexion step ups, squats, lunges, bridging, SLS and balance exercises

TIME	AIMS	PRECAUTIONS	SUGGESTIONS
At 6 weeks should have full ROM – Please complete and return data set to ACLR clinic			
6 TO 12 WEEKS	Progress as appropriate	NOTE : graft weakest 8-12 weeks as it goes through a period of revascularisation	Progress as appropriate
12 WEEKS - Seen in ACLR review clinic			
3 MONTHS ONWARDS	Equalise strength, power and co-ordination to opposite limb Specific skills training Begin open and multiplane activities as appropriate to the individual	Progress should be based on functional testing and individual capabilities	Progress strength work as able – open chain exercise at the therapists discretion Progress proprioceptive work Jogging, running, direction changes, bounding and plyometrics as capable / appropriate
6 MONTHS – Please complete and return ACLR data set to the review clinic. Consider progression of rehab and return to sport based on functional testing			
9 MONTHS – Consider return to sport / competition based on functional testing			
12 MONTHS – Review in ACL clinic			

Appendix 2: South East Wales Research Ethics Committee (SEWREC) approval letter

GIG CYMRU NHS WALES | Canolfan Gwasanaethau Busnes | Business Services Centre

South East Wales Research Ethics Committee - Panel D

Telephone: 02920 376822/6823

01 November 2010

Mr Robert Letchford
Clinical Specialist Physiotherapist / PhD Student
Aneurin Bevan Health Board / Cardiff University
Physiotherapy Department
Royal Gwent Hospital
Cardiff Road, Newport
NP20 2UB

Dear Mr Letchford

Study Title:	**An Investigation of Functional Recovery and Knee Stability Following Anterior Cruciate Ligament Reconstruction.**
REC reference number:	**10/WSE04/48**

Thank you for your letter of 18 October 2010, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair, Dr K Craig.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation [as revised], subject to the conditions specified below.

Ethical review of research sites

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

Conditions of the favourable opinion

The favourable opinion is subject to the following conditions being met prior to the start of the study.

Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.

Canolfan Gwasanaethau Busnes
Ty Churchill
17 Ffordd Churchill
Caerdydd, CF10 2TW
Ffôn: 029 20 376820 WHTN: 1809
Ffacs: 029 20 376826

Business Services Centre
Churchill House
17 Churchill Way
Cardiff, CF10 2TW
Telephone: 029 20 376820 WHTN: 1809
Fax: 029 20 376826

rhan o Bwrdd Iechyd Lleol Addysgu Powys / part of Powys Teaching Local Health Board

Protocol Flow Chart	1	23 August 2010
Confirmation of funding from rcbcwales		27 July 2010
Appointment and invitation letter	2	18 October 2010
Referees or other scientific critique report	Research Scrutiny Committee - Aneurin Bevan Health Board	12 July 2010
Referees or other scientific critique report	Research Risk Review Committee - Aneurin Bevan Health Board	16 July 2010
Evidence of insurance or indemnity		27 July 2010
Confirmation and appointment letter	2	18 October 2010

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees (July 2001) and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

Now that you have completed the application process please visit the National Research Ethics Service website > After Review

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the website.

The attached document *"After ethical review – guidance for researchers"* gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Progress and safety reports
- Notifying the end of the study

The NRES website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

We would also like to inform you that we consult regularly with stakeholders to improve our service. If you would like to join our Reference Group please email referencegroup@nres.npsa.nhs.uk.

For NHS research sites only, management permission for research ("R&D approval") should be obtained from the relevant care organisation(s) in accordance with NHS research governance arrangements. Guidance on applying for NHS permission for research is available in the Integrated Research Application System or at http://www.rdforum.nhs.uk.

Where the only involvement of the NHS organisation is as a Participant Identification Centre (PIC), management permission for research is not required but the R&D office should be notified of the study and agree to the organisation's involvement. Guidance on procedures for PICs is available in IRAS. Further advice should be sought from the R&D office where necessary.

Sponsors are not required to notify the Committee of approvals from host organisations.

It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
Investigator CV	R H Letchford	23 August 2010
Investigator CV	V Sparkes - Not dated	
Investigator CV	R van Deursen	20 October 2010
Protocol	1.1	23 June 2010
Telephone Confirmation Letter	1	23 August 2010
Visual Analogue Score - Pain Intensity & PGIC score		
REC application	IRAS 3.0	06 September 2010
Covering Letter	R Letchford	23 August 2010
Letter from Sponsor		01 September 2010
Questionnaire: The Lysholm Knee Scale		
Advertisement	1	23 August 2010
GP/Consultant Information Sheets	1	23 August 2010
Participant Information Sheet: Patient	2	18 October 2010
Response to Request for Further Information		18 October 2010
Participant Information Sheet: Healthy Participant	2	18 October 2010
Participant Consent Form: Patient	2	18 October 2010
Participant Consent Form: Healthy Participant	2	18 October 2010
Questionnaire: IKDC subjective knee form		
Questionnaire: Tegner Activity Score		
Questionnaire: Cincinnati Knee rating system		
Questionnaire: Marx Activity Scale		

10/WSE04/48	Please quote this number on all correspondence

Yours sincerely

P.P.

Dr K J Craig
Chair

Email: jagit.sidhu@bsc.wales.nhs.uk

Enclosures:	"After ethical review – guidance for researchers" - *SL- AR2*
Copy to:	*R&D Department for Cardiff University* *R&D Department for Aneurin Bevan Health Board*

GIG CYMRU NHS WALES | Bwrdd Iechyd Aneurin Bevan Health Board

Research & Development
Research Scrutiny Committee
Tel: 01633 234768

Robert Letchford
Clinical Specialist Physiotherapist
Physiotherapy Dept
Royal Gwent Hospital

Ref: RSC.31.10
12th July 2010

Dear Mr Letchford
An investigation of Functional Recovery and knee stability following Anterior Cruciate ligament reconstruction
Reg: RD/879/10

The Research Scrutiny Committee reviewed your project at their meeting held on 7th July 2010 and would like to thank you for attending with your supervisor, Dr Van Deursen.

It was agreed your project was well thought out and approved.

I wish you every success with this project.

Please note that no substantial changes or amendments can be made to the protocol without notifying the Trust Research & Development Office.

Kind Regards

p.p.
Professor Sue Bale
Chairman
Research Scrutiny Committee

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Appendix 3: Patient information Sheet

Patient information sheet Version 1.1 23rd August 2010
A study of functional recovery following Anterior Cruciate Ligament Reconstruction.

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Talk to others about the study if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

What is the purpose of the study?
Anterior Cruciate Ligament (ACL) reconstruction is a proven method for improving function after injury, but there remains a lot we do not know about it. This research study aims to measure changes in function following the operation and attempts to identify areas of physiotherapy that could improve the outcome of the operation.

Why have I been chosen?
We are studying adults who are having an ACL reconstruction for the first time, and hope to get 100 volunteers over the next year.

Do I have to take part?
No. It is up to you to decide whether or not to take part. If you do, you will be given this information sheet to keep and be asked to sign a consent form. You are still free to withdraw at any time and without giving a reason. A decision to withdraw at any time, or a decision not to take part, will not affect the standard of care you receive.

What will happen to me if I take part?
Our current service asks you to attend an appointment before your operation, and again at 6 weeks, 3, 6, 12 and 24 months after the operation. This 30 minute appointment is used to assess your knee using questionnaires and movement tests to keep you, your surgeon and your Physiotherapist informed of your progress.

Participation in the research study will add 1 extra appointment after the surgery and alter the timing slightly (1, 2, 3, 6, 12 and 24 months). Every effort is made for these appointments to be at the same time as your Physiotherapy appointments, meaning in most circumstances there will be no greater commitment on your time.

What tests will I need to do?
The following tests are used safely throughout the world in patients with ACL injuries; they are quick and simple to complete:
5 short paper questionnaires that should take no longer than 10 minutes.
Video of movements – We will collect video clips of you walking 6 meters, squatting on one leg and when safe, hopping on either leg.
KT2000 – This is a machine that takes a simple measure of the movement in your knee.

During testing you will be required to wear shorts and training shoes.

What other information will you need?
We will collect information from your medical notes with regard to your injury, such as when you injured your knee, what ligaments you injured, how you were treated etc... These will be studied to see if they affect the outcome and could tell us how to better manage injury in the future. If this information is not in your notes we may ask you.

What will happen to the Video?
The digital video clips will be used to take measures of your movements. They will be stored securely and anonymously on our electronic database until we have analysed them when they will be destroyed, unless you give us permission to keep them when they will be used for teaching and educational purposes. You will be asked to sign a form stating how you will allow us to use these videos. We will blur the region of the clip around you face so that you are not identifiable.

Expenses and payments
There is no payment available for participation in this study. Payment to cover travel for the one extra appointment, at Aneurin Bevan Health Board mileage rates, will be available on request.

What do I have to do?
Attend the review appointments, where you will fill in the questionnaires and complete the tests as stated above. If you are unable to attend please keep us informed and we will make arrangements for appointments to suit you.

What are the possible disadvantages and risks of taking part?
There are no increased risks associated with participation in the study as all the tests are ones that you would do in our standard service. The hop test carries a low risk of injury however prior to completing this test you will be have to be able to achieve certain other tests in order to be allowed to complete the hopping test. If at any time it is thought to be unsafe, or you do not wish to do so, the test will not be carried out.

What are the possible benefits of taking part?
During the study there will be no difference in the service you receive apart from the extra visit. However, if we are successful in identifying areas for improvements in rehabilitation these would be made available to you after the study period. The greater benefits will be for those in your situation in the future who will be able to be treated in the light of our findings.

What if there is a problem?
Any complaint about the way you have been dealt with during the study or any possible harm you might suffer will be addressed. There are more details in part 2.

If the information in Part 1 has interested you and you are considering participation, please read the additional information in Part 2 before making any decisions

PART 2

What will happen if I don’t want to carry on with the study?
If you withdraw from the study, we will destroy all your identifiable samples, but we will need to use the data collected up to your withdrawal

What if I am harmed?
In the event that something does go wrong and you are harmed during the research study there are no special compensation arrangements. If you are harmed and this is due to

someone's negligence then you may have grounds for a legal action for compensation against Aneurin Bevan Health Board, the normal National Health Service complaints mechanisms will still be available to you.

If you have a concern about any aspect of this study, you should ask to speak with the researchers who will do their best to answer your questions **(Contact; Robert Letchford Research Physiotherapist 01633 234416)**. If you remain unhappy and wish to complain formally, you can do this through the NHS Complaints Procedure **(Contact; Nikki Cook, Operational Manager, Physiotherapy department 01633 238389).**

Will my taking part in the study be kept confidential?

Yes. All the information about your participation in this study will be kept confidential. Any information about you which leaves the hospital will have your name and address removed so that you cannot be recognised from it.

What will happen to the results of the research study?

The results will be presented to the staff involved in the service, and to national and international audiences through conferences and publication in medical journals. You will not be identified in any report/publication unless you have consented to the release of such information. We will send you information on our findings.

Who is organising and funding the research?

The study is part of a PhD research degree at Cardiff University, funded by a NHS Wales Grant (RCBC Wales), and affiliated to the Arthritis Research UK Biomechanics and Bioengineering Centre.

Who has reviewed the study?

This study was given a favourable ethical opinion for conduct in the NHS by :
Cardiff University
Research Capacity Building Collaboration Wales
Aneurin Bevan Health Board Research Scrutiny Committee
Aneurin Bevan Health Board Risk Review Committee
National Research Ethics Service

For further information please contact

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Tel 01633 234417
e-mail Robert.letchford@wales.nhs.uk

Appendix 4: Consent form

PATIENT CONSENT FORM

Version Number 1.1 23rd August 2010

Royal Gwent Hospital

Name of Patient ………………………………………………………………

Name of Clinician………………………………………………………………

Study of the functional outcome of anterior cruciate ligament (ACL) reconstruction

Statement by Patient

- I confirm that I consent to take part in a trial/study for the evaluation of knee function following ACL reconstruction. ☐
- Details of the trial have been explained to me by the above-named clinician including the benefits, major risks and discomfort it may entail. I have read and understand the information leaflet dated 23rd August 2010 (Version1.1). I have had the opportunity to consider the information, ask questions and had these answered satisfactorily. ☐
- I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐
- I understand that relevant information from my medical notes and data collected may be looked at by responsible individuals from Aneurin Bevan Health Board, Cardiff University where it is relevant to my taking part in this research, I give permission for these individuals to have access this data. ☐
- I consent to the taking / storage of video for the following purposes; ☐
- This research study ☐
- Teaching healthcare personnel ☐
- Material that includes publication e.g. posters, leaflet
- I agree to my GP being informed of my participation in the study ☐
- I am willing to take part in this study. ☐

Signed ………………………………… Date …………….

Statement by Clinician.

I have explained the nature and the purpose of the study to the above-named patient and believe that the patient understands what the study involves.

Signed ………………………………………… Date …………….

The End